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UREĐIVAČKA POLITIKA

Časopis Energija znanstveni je i stručni časopis s dugom tradicijom više od 50 godina. Pokriva područje elektroprivredne djelatnosti i energetike. Časopis Energija objavljuje izvorne znanstvene i stručne članke širokoga područja interesa, od specifičnih tehničkih problema do globalnih analiza procesa u području energetike.

U vrlo širokom spektru tema vezanih za funkcioniranje elektroprivredne djelatnosti i općenito energetike u tržišnim uvjetima i općoj globalizaciji, časopis ima poseban interes za specifične okolnosti ostvarivanja tih procesa u Hrvatskoj i njezinu regionalnom okruženju. Funkcioniranje i razvoj elektroenergetskih sustava u središnjoj i jugoistočnoj Europi, a posljedično i u Hrvatskoj, opterećeno je mnogobrojnim tehničko-tehnološkim, ekonomskim, pravnim i organizacijskim problemima. Namjera je časopisa da postane znanstvena i stručna tribina na kojoj će se kritički i konstruktivno elaborirati navedena problematika i ponuditi rješenja.

Časopis je posebno zainteresiran za sljedeću tematiku: opća energetika, tehnologije za proizvodnju električne energije, obnovljivi izvori i zaštita okoliša; korištenje i razvoj energetske opreme i sustava; funkcioniranje elektroenergetskoga sustava u tržišnim uvjetima poslovanja; izgradnja elektroenergetskih objekata i postrojenja; informacijski sustavi i telekomunikacije; restrukturiranje i privatizacija, reinženjering poslovnih procesa; trgovanje i opskrba električnom energijom, odnosi s kupcima; upravljanje znanjem i obrazovanje; europska i regionalna regulativa, inicijative i suradnja.

Stranice časopisa podjednako su otvorene iskusnim i mladim autorima, te autorima iz Hrvatske i inozemstva. Takva zastupljenost autora osigurava znanje i mudrost, inventivnost i hrabrost, te pluralizam ideja koje će čitatelji časopisa, vjerujemo, cijeniti i znati dobro iskoristiti u svojem profesionalnom radu.

EDITORIAL POLICY

The journal Energy is a scientific and professional journal with more than a 50-year tradition. Covering the areas of the electricity industry and energy sector, the journal Energy publishes original scientific and professional articles with a wide area of interests, from specific technical problems to global analyses of processes in the energy sector.

Among the very broad range of topics relating to the functioning of the electricity industry and the energy sector in general in a competitive and globalizing environment, the Journal has special interest in the specific circumstances in which these processes unfold in Croatia and the region. The functioning and development of electricity systems in Central and South East Europe, consequently in Croatia too, is burdened with numerous engineering, economic, legal and organizational problems. The intention of the Journal is to become a scientific and professional forum where these problems will be critically and constructively elaborated and where solutions will be offered.

The Journal is especially interested in the following topics: energy sector in general, electricity production technologies, renewable sources and environmental protection; use and development of energy equipment and systems; functioning of the electricity system in competitive market conditions; construction of electric power facilities and plants; information systems and telecommunications; restructuring and privatization, re-engineering of business processes; electricity trade and supply, customer relations, knowledge management and training; European and regional legislation, initiatives and cooperation.

The pages of the Journal are equally open to experienced and young authors, from Croatia and abroad. Such representation of authors provides knowledge and wisdom, inventiveness and courage as well as pluralism of ideas which we believe the readers of the Journal will appreciate and know how to put to good use in their professional work.

UVOD
INTRODUCTION

Poštovani čitatelji!
Pred sobom imate novi, treći, broj časopisa Energija u 2008. godini. Energetski sektor danas obiluje vrlo interesantnim temama za stručnu i znanstvenu javnost i to u nizu različitih aspekata počevši od restrukturiranja energetskog sektora, strategija razvoja, izgradnje velikih energetskih infrastrukturnih projekata te zaštite okoliša. Struktura tema podjednako je zanimljiva za svaku zemlju posebno kao i za regiju, odnosno skupinu zemalja. Nema sumnje da će se razmatranja o energetskom sektoru intenzivirati u jugoistočnoj Europi, a napose u Hrvatskoj, pa vas pozivamo da iznesete svoja razmišljanja ko i rezultate istraživanja o bilo kojem bitnom aspektu energetskog sektora.

U ovom broju časopisa Energija objavljujemo članke koji su na određeni način vezani uz globalni energetski te elektroenergetski sektor, a isto tako i članke iz pojedinih specijalističkih područja elektrotehnike:

— Liberalizacija tržišta električne energije – ispunjava li očekivanja?
— Rad fotonaponskog parka na otoku Kreti,
— Procjena rizika stradavanja radnika distribucije,
— Napon nul-vodiča mreže niskog napona za vrijeme zemljospoja u mreži srednjeg napona,
— Smanjenje udarnih struja uklopa trofaznog energetskog transformatora.

U prvom članku u ovom broju časopisa Energija iznesena je jedna analiza uspješnosti reforme elektroenergetkog sektora. Naime, kako je to u članku i naglašeno, osnovni deklarativni cilj reformi industrije električne energije, odnosno liberalizacije tržišta električne energije, bio je i jest podizanje djelotvornosti elektroenergetskog sektora, prije svega radi povećanja konkurentnosti gospodarstva. Od liberalizacije tržišta električne energije očekivalo se: sniženje cijena električne energije, podizanje razine usluge, smanjivanje razlike u cijenama među državama, mogućnost biranja opskrbljivača za svakog kupca i povećanje učinkovitosti sektora kroz smanjenu potrebu za izgradnjom i održavanjem rezervnih kapaciteta. U radu se tako istražuje i analizira koliko su navedeni ciljevi liberalizacije tržišta električne energije ostvareni i ostvarivi, koliko je uspješan pomak organizacijske strukture industrije električne energije od monopolske prema konkurencijskoj, odnosno ispunjava li liberalizacija tržišta električne energije očekivanja.
Od profesora Papazogloua s Electrical Engineering Department Technological Educational Institute (TEI) na otoku Kreti stiže nam novi članak koji opisuje performanse jedne izgrađene fotonaponske elektrane vršne snage 170 kWp. Rad fotonaponskih ćelija anailiziran je ti-

Dear Readers,
You have before you the third issue of the journal Energija for the year 2008. Today, the energy sector abounds in highly interesting topics for the professional and scientific public, including the restructuring of the energy sector, development strategy, the construction of large energy infrastructure projects and environmental protection. These topics are equally interesting for each country individually as well as for a region or group of countries. Undoubtedly, discussions concerning the energy sector will intensify in South Eastern Europe, especially Croatia, and therefore we invite you to present your ideas and research results on any aspect of the energy sector.

In this issue of the journal Energija, we are publishing articles that in a specific way are connected with the global energy and electrical energy sectors, as well as articles from individual specialized areas of electrical engineering:

— Liberalization of the Electricity Market – Is It Meeting Expectations?
— The Performance of a Photovoltaic Park on the Island of Crete,
— Assessment of Risk to Distribution Workers,
— The Neutral Conductor Voltage in a Medium-Voltage Network during a Ground Fault,
— Reduction of the Inrush Currents of Three-Phase Power Transformers.

In the first article in this issue of the journal Energija, an analysis is presented of the degree of success that has been achieved by reforms of the electrical energy sector. As particularly emphasized in the article, the fundamental declarative goal of the reform of the electricity industry, i.e. liberalization of the electricity market, has been to raise the efficiency of the electrical energy sector, primarily for the purpose of increasing the competitiveness of the economy. The expectations from the liberalization of the electricity markets included the lowering of electricity prices, raising the level of services, reducing the level of prices among countries, the opportunity for each customer to choose a supplier, and increasing the efficiency of the sector through reducing the need for building and maintaining reserve capacities. On the basis of investigation and analysis, an assessment is presented of the extent to which the aforementioned goals of the liberalization of the electricity market have been achieved and how successful the shift in the organizational structure of the electrical power industry from monopolistic to competitive has been, i.e. whether the liberalization of the electricity market has met expectations.
A new article has arrived from Prof. Papazoglou of the Electrical Engineering Department, Technological Educational Institute (TEI) of Crete, describing the performance of a photovoltaic park with a peak power of 170 kWp. The operation of the photovoltaic park was analyzed over the period of a year.

jekom godine dana pa se na temelju rezultata izračunavao stupanj djelovanja (performance ratio) te različiti gubici snage (temperaturni, onečišćenje, unutarnji gubici u mreži, energetska elektronika, raspoloživost i međuspoj mreže). Ne treba posebno spominjati kako su rezultati navedeni u članku vrlo zanimljivi.

U ovom broju časopisa Energija imamo i temu vezanu uz analizu rizika stradavanja radnika na održavanju postrojenja srednjeg napona distribucijske tvrtke koja dolazi od autora koji je i zaposlen u distribucijskoj tvrtki. Članak je proizašao je iz niza istraživanja (povrede na radu, vrijeme na održavanju postrojenja, kvarovi sa zemljom i kvarovi uzemljivača) i predstavlja skup svih prikupljenih relevantnih informacija o ugrozi radnika.
Članak je interesantan i poradi toga što je naglašena potreba analize mogućih događaja unaprijed, čime se potencijalne opasnosti koje mogu ugroziti zdravlje i život radnika za vrijeme rada na održavanju praktički kvantificiraju. Upravljanje takvim rizicima postat će sve više zadaća svih tvrtki, i iz iz humanih razloga, kao i iz razloga smanjenja troškova pogona i održavanja.

Članak kategoriziran kao izvorni znanstveni članak obrađuje temu vezanu uz zemljospoj u trafostanici srednji napon/niski napon. Naime, od svih zemljospojeva koji se mogu pojaviti u mrežama srednjeg napona sa stanovišta sigurnosti ljudi i opreme najproblematičniji je zemljospoj u trafostanici srednji napon/niski napon s obzirom da je uzemljivački sustav mreže niskog napona direktno povezan s uzemljivačem trafostanice pa se svako povećanje potencijala uzemljivača trafostanice direktno prenosi preko nul-vodiča u instalaciju potrošača. U radu je prezentiran računski model za analizu napona nul-vodiča u realnim distribucijskim mrežama te je prikazana analiza dvije karakteristične distribucijske mreže položene na kraškom terenu. Poseban doprinos predstavlja i usporedba s rezultatima mjerenja na terenu.

Posljednji članak u kojemu je opisan jedan matematički model uklopa trofaznog transformatora uz uračunate efekte petlje histereze i zaostalog magnetskog toka. Naime, udarne struje koje se javljaju prilikom uklopa energetskog transformatora mogu doseći vrlo velike iznose te uzrokovati mnogobrojne probleme u elektroenergetskom sustavu. Također je opisan i sustav za mjerenje zaostalog magnetskog toka na osnovi mjerenja napona prethodnog isklopa, pa je u radu predložen i algoritam za određivanje najpovoljnijeg trenutka uklopa. Posebno važan zaključak u radu je da predloženo rješenje eliminira pojavu udarnih struja koje su veće od iznosa nazivne struje transformatora.

Članke u ovom broju časopisa Energija potpisuje deset autora iz sveučilišne zajednice, ali i iz prakse, što je, sasvim sigurno, rezultiralo i kvalitetnim člancima.

Glavni urednik:
Mr. sc. Goran Slipac

On the basis of the results, the performance ratio and various power losses (temperature, soiling, internal network, power electronics, grid availability and interconnection) were calculated. Needless to say, the results presented in this article are of great interest.

In the current issue of the journal Energija, we also have a topic connected with the analysis of the risk of worker injury in specific facilities of medium-voltage distribution companies, written by an author who is employed by a distribution company. The article is the result of a series of investigations (injuries at work, time spent on equipment maintenance, ground faults and failures in the grounding system), and represents all the relevant information collected on the hazards to workers. The article is also interesting because it underscores the need for analyzing the potential events in advance, so that eventual hazards that can endanger the health and life of workers during working hours can be quantified. Such risk management will become an increasingly important task for all companies, both for humane reasons as well as reducing the costs of equipment and maintenance.

An article categorized as an original scientific paper discusses a topic connected with ground faults in medium-voltage/low-voltage substations. Of all the ground faults that can occur in medium-voltage networks, from the standpoint of human and equipment safety the most problematic is a ground fault in a medium-voltage/low-voltage substation since the grounding system of a low-voltage network is directly connected to the grounding electrode of the substation and each increase in the potential of the grounding electrode of the substation is directly transmitted via the neutral conductor into the customer's installation. A computer model for the analysis of the neutral conductor voltage in actual distribution networks is presented, with an analysis of two characteristic distribution networks located on karstic terrain. A particular contribution is represented by the comparison of the results of the computer model with the results of measurements on the terrain.

The last article presents a description of a mathematical model of the energization of a three-phase power transformer with the calculated effects of hysteresis and remanent magnetic flux. The inrush currents that occur during the energization of a three-phase power transformer can reach very high values and cause many problems in an electrical power system. A system for the measurement of remanent magnetic flux based upon the measurement of the integration of the secondary voltage during the previous de-energization is described, and an algorithm is presented for the determination of the optimal instant of energization. A particularly important conclusion in the article is that the proposed solution eliminates the occurrence of inrush currents which are greater than the values of the rated transformer current.

The articles in this issue of the journal Energija are signed by ten authors from academia as well as the field, which has certainly resulted in quality presentations.

Editor-in-chief:
Goran Slipac, MSc

LIBERALIZACIJA TRŽIŠTA ELEKTRIČNE ENERGIJE – ISPUNJAVA LI OČEKIVANJA?

LIBERALIZATION OF THE ELECTRICITY MARKET – IS IT MEETING EXPECTATIONS?

Ivan Tominov, Zagreb, Hrvatska

Osnovni deklarativni cilj reformi industrije električne energije, odnosno liberalizacije tržišta električne energije, bio je i jest, podizanje djelotvornosti elektroenergetskog sektora, prije svega radi povećanja konkurentnosti gospodarstva. Od liberalizacije tržišta električne energije očekivalo se: sniženje cijena električne energije, podizanje razine usluge, smanjivanje razlike u cijenama među državama, mogućnost biranja opskrbljivača za svakog kupca i povećanje učinkovitosti sektora kroz smanjenu potrebu za izgradnjom i održavanjem rezervnih kapaciteta.
U ovom radu istražuje se i analizira koliko su navedeni ciljevi liberalizacije tržišta električne energije ostvareni i ostvarivi, koliko je uspješan pomak organizacijske strukture industrije električne energije od monopolske prema konkurencijskoj, odnosno ispunjava li liberalizacija tržišta električne energije očekivanja. Temeljem procjene odnosa troškova i koristi od liberalizacije tržišta električne energije može se reći da liberalizacija neće ostvariti glavni cilj zbog kojeg je pokrenuta, a to je sniženje cijene električne energije. Nije ostvaren ni cilj izjednjačavanja cijena, jer i dalje egzistira velika razlika u cijenama električne energije među državama. Nema signifikantnog pomaka organizacijske strukture industrije električne energije od monopolske prema konkurencijskoj. Pozitivni pomaci učinjeni su na podizanju razine kvalitete usluge, povećanju učinkovitosti sektora kroz smanjenu potrebu za izgradnjom i održavanjem rezervnih kapaciteta i u formalnom otvaranju tržišta. Ovi nalazi istraživanja potvrđuju hipotezu iznesenu u Uvodu da glavni ciljevi liberalizacije tržišta električne energije nisu ostvareni, pa se može konstatirati da liberalizacija tržišta električne energije ne ispunjava očekivanja. Što više, prema sadašnjem stanju reformi i prema tendencijama u tim procesima ti ciljevi, onako kako su na početku reformi zamišljeni i zacrtani, nisu ni ostvarivi.
The fundamental declarative goal of the reform of the electrical power industry, i.e. the liberalization of the electricity market, has been and remains to raise the efficiency of the electrical power sector, primarily for the purpose of increasing the competitiveness of the economy. The following had been expected from the liberalization of the electricity market: reduction in the price of electricity, improvement in the level of service, reduction in the differences in prices among countries, the option for each customer to choose a supplier, and an increase in the efficiency of the sector by reducing the need for the construction and maintenance of reserve capacities.
This work presents an investigation and analysis of the extent to which these goals for the liberalization of the electricity market have been achieved and are achievable, how successful the shift has been from a monopolistic organizational structure of the electrical power industry to a competitive structure, i.e. whether the liberalization of the electricity market has met expectations. Based upon assessment of the cost-benefit ratio from the liberalization of the electricity market, it can be said that liberalization will not achieve the primary goal for which it was initiated, which is reduction of the price of electricity. The goal of making prices uniform was also not achieved because there are still great differences in the prices of electricity among countries. There has been no significant shift in the organizational structure of the electrical power industry from monopolistic to competitive. Positive shifts have been achieved in raising the level of the quality of services, increasing the efficiency of the sector by reducing the need for the construction and maintenance of reserve capacities, and in the formal opening of the markets. These research findings confirm the hypothesis presented in the introduction to this work that the primary goals of the liberalization of the electricity markets have not been achieved. It can be concluded that the liberalization of the electricity market has not fulfilled expectations. Moreover, according to the current status of the reforms and the tendencies in these processes, these goals have not been achieved in the manner in which the initial reforms were imagined and defined.

Ključne riječi: deregulacija, liberalizacija, regulacija, tržište električne energije
Key words: deregulation, electricity market , liberalization, regulation

1 UVOD

Električna energija kao sveprisutan i gotovo nezamjenjiv energent, služi zadovoljenju mnogih, poglavito elementarnih potreba u svim područjima života. Trošak električne energije sastavni je dio troškova izrade svih proizvoda i usluga i troškova života. Znači da cijena električne energije direktno i indirektno određuje razinu životnog standarda. Direktno kroz potrošnju električne energije u kućanstvima, a indirektno preko cijena svih proizvoda i usluga. Na cijenu električne energije u znatnoj mjeri utječe efikasnost poslovanja elektroenergetskog sektora. Upravo težnja za većom efikasnošću osnovni je pokretač reformi u industriji električne energije diljem svijeta.

U elektroenergetskom sektoru tradicionalno su dominirali monopoli. Tako je funkcionirala industrija električne energije sve do početka 1990-ih godina, kad je ovaj sektor (kao i sektori transporta i telekomunikacija), potpomognut općim trendom deregulacije, počeo odmicati od monopolističke strukture prema više konkurencijskoj.

Osnovni deklarativni cilj poduzetih reformi, odnosno liberalizacije tržišta električne energije, bio je i jest podizanje djelotvornosti elektroenergetskog sektora, prije svega radi povećanja konkurentnosti gospodarstva. Od liberalizacije tržišta električne energije očekivalo se: sniženje cijena električne energije, podizanje razine usluge, smanjivanje razlike u cijenama među državama, mogućnost biranja opskrbljivača za svakog kupca i povećanje učinkovitosti sektora kroz smanjenu potrebu za izgradnjom i održavanjem rezervnih kapaciteta.

U ovom radu nastoji se istražiti, analizom procesa reformi industrije električne energije u svijetu, koliko su navedeni ciljevi liberalizacije tržišta električne energije ostvareni i ostvarivi, koliko je uspješan pomak organizacijske strukture industrije električne energije od monopolske prema konkurencijskoj, odnosno ispunjava li liberalizacija tržišta električne energije očekivanja.

Rad je strukturiran tako da se nakon Uvoda iznose teoretski aspekti liberalizacije tržišta električne energije. Tu se uz definiranje osnovnih pojmova tržišta obrađuje tržišni mehanizam i elastičnost potražnje električne energije. Na kraju se iznose teoretski argumenti za deregulaciju i liberalizaciju.

U trećem dijelu analiziraju se procesi reforme industrije električne energije, odnosno razvoj

1 INTRODUCTION

Electricity as an omnipresent and nearly irreplaceable energy source serves to meet many needs, some of which are elementary, in all areas of life. Electricity costs are an integral part of the costs of producing all products and services, as well as living expenses. This means that the price of electricity directly and indirectly determines the level of the standard of living, directly through electricity consumption in households and indirectly through the prices of all products and services. The price of electricity is significantly influenced by the efficiency of the operations of the electrical power sector. The aspiration to increase efficiency has actually been the basis for initiating reforms in the electrical power industry throughout the world.

Monopolies have traditionally dominated the electrical power sector. This is how the electrical power industry functioned until the early 1990s, when this sector (as well as the transport and telecommunications sectors) began, within the general trend toward deregulation, to move away from the monopolistic structure toward greater competitiveness.

The fundamental declarative goal of the undertaken reforms, i.e. the liberalization of the electricity market, has been and remains to raise the efficiency of the electrical power sector, primarily for the purpose of increasing the competitiveness of the economy. The following had been expected from the liberalization of the electricity market: reduction in the price of electricity, improvement in the level of service, reduction in the price differences among countries, the option for each customer to choose a supplier, and an increase in the efficiency of the sector by reducing the need for the construction and maintenance of reserve capacities.

In this work, through an analysis of the processes of the reform of the electrical power industry in the world, an attempt is made to assess the extent to which the stated goals of the liberalization of the electricity market have been and are being achieved, and how successful the shift in the organizational structure of the electrical power industry has been from monopolistic toward competitive, i.e. whether the liberalization of the electricity market has fulfilled expectations.

The present article is structured in such a manner that following the introduction, the theoretical aspects of the liberalization of the electricity market are presented. In addition to defining the basic market concepts, market mechanisms and the elasticity of electricity demand are analyzed. In the conclusion, theoretical arguments are presented for deregulation and liberalization.

tržišta električne energije u svijetu. Naglasak je stavljen na stvaranje unutarnjeg tržišta električne energije u Europskoj uniji, jer je to asocijacija kojoj mi težimo, uz poseban osvrt na tranzicijske zemlje, SAD i Hrvatsku.

U četvrtom dijelu obrazlaže se nužnost povećane regulacije u novim uvjetima poslovanja i analiziraju se novi oblici regulacije u elektroenergetskom sektoru.

U petom dijelu razmatraju se problemi koji stoje na putu bržeg i uspješnijeg otvaranja tržišta električne energije, procjenjuje odnos troškova i koristi i analiziraju efekti liberalizacije tržišta električne energije.

Na kraju se iznose zaključna razmatranja o procesima reformi industrije električne energije i njihovoj perspektivi.

2 TEORETSKI ASPEKTI LIBERALIZACIJE TRŽIŠTA ELEKTRIČNE ENERGIJE

2.1 Uvod

Makroekonomika se bavi općom ravnotežom gospodarstva kao cjeline, dovodeći u ravnotežu makroekonomske pokazatelje, kao što su inflacija, nezaposlenost i cijena kapitala. Mikroekonomika se bavi optimalizacijom ponašanja potrošača i proizvođača te analizira ravnotežu cijena i količina I njihovu učinkovitost na tržištu.

Ne postoji jamstvo da će slobodna tržišta nužno dovesti do učinkovitosti. Karakteristike tržišta električne energije mogu dovesti do neučinkovitih cijena i količina. Neučinkovitost tržišta i nametanje regulacije proizvode društvene gubitke.

Postoji niz tipova tržišta, koji ovise o broju sudionika na strani ponude i na strani potražnje i o njihovoj interakciji. U slučaju savršene konkurencije interakcija između kupaca i prodavača rezultira tržišnom cijenom koja je jednaka trošku proizvodnje zadnje prodane jedinice. To je ekonomski učinkovito rješenje. U slučaju monopola jedan jedini prodavač može smanjiti količinu dizanjem cijene iznad troška proizvodnje.

Industrija električne energije obuhvaća najmanje četiri gospodarske aktivnosti: proizvodnju, prijenos, distribuciju i opskrbu električnom energijom. Ove aktivnosti mogu biti objedinjene ili odvojene. Kad su te aktivnosti objedinje-

In the third section, the processes of the reform of the electrical power industry are analyzed, i.e. the development of the electricity markets in the world. Emphasis is placed on the creation of an internal electricity market in the European Union because this is an association which we aspire to join, with particular attention to countries in transition, the United States and Croatia.

In the fourth section, reasons are cited for the necessity of increasing regulation under the new operating conditions and there is an analysis of the new forms of regulation in the electrical power sector.

In the fifth section, problems are discussed that are standing in the way of the more rapid and successful opening of the electricity markets, the cost-benefit ratio is assessed, and the effects of the liberalization of the electricity markets are analyzed.

At the end, final conclusions are discussed regarding the processes of the reform of the electrical power industry and their prospects.

2 THEORETICAL ASPECTS OF THE LIBERALIZATION OF THE ELECTRICITY MARKET

2.1 Introduction

Economics focuses upon optimalization and equilibrium. Macroeconomics concerns the general equilibrium of the economy as a whole, bringing macroeconomic indices into equilibrium, such as inflation, unemployment and the price of capital. Microeconomics concerns the optimalization of consumer and producer behavior and examines whether the balanced prices and quantities observed on each market are economically efficient.

There is no guarantee that the free market will necessarily be led to efficiency. The characteristics of the electricity market can lead to inefficient prices and quantities. Inefficient markets and imposed regulations produce losses for the society.

There are many types of markets, depending upon the number of participants on the supply side and the demand side, as well as their interaction. In the case of perfect competition, interaction among many customers and vendors results in a market price that is equal to the cost of the production of the final unit sold. This is an economically efficient solution. In the case of a monopoly, a single vendor can reduce the quantity, thereby driving the price above production costs.

The electrical power industry includes at least four economic activities: the production, transmission, ne na jednom tržištu onda postoji samo jedan opskrbljivač električnom energijom, odnosno monopolist. Tržišta električne energije određena su ili monopolom ili konkurencijom. Tradicionalno su u industriji električne energije dominirali državni i lokalni monopoli s regulacijom cijena kako bi se potaknulo ekonomski učinkovito ponašanje.

2.2 Tržišni mehanizam

Najjednostavniji način opisivanja tržišne interakcije između kupaca i prodavača je da se pretpostavi postojanje dražbe. Hipotetski, na dražbi se obavlja sljedeće:

— objavljuje raspon cijena i kupcima i prodavačima tražeći od sudionika na tržištu objavu količina koje su spremni kupiti ili prodati po svakoj ponuđenoj cijeni i
— određuje cijenu koja izjednačava količinu potražnje kupaca s količinom koju nude prodavači.

Naravno, većina tržišta funkcionira bez točno određenog dražbovatelja. Međutim, u mnogim elektroenergetskim sustavima s podijeljenim aktivnostima, neovisni operator tržišta djeluje kao dražbovatelj.

Potražnja količine po svakoj određenoj cijeni je raspored potražnje ili, jednostavno potražnja. Količina koja se nudi po svakoj cijeni je raspored ponude ili, jednostavno, ponuda. Potražnja i ponuda grafički su prikazane na slici 1. Cijena je prikazana na vertikalnoj osi (y), a količina na vodoravnoj osi (x). Npr., da bi se prikazalo tržište električne energije, okomita os predstavlja cijenu po megavat satu [MWh], a vodoravna os predstavlja količinu u [MWh].

distribution and supply of electricity. These activities can be bundled or separate. When these activities are bundled, there is only one supplier of electricity, i.e. the monopolist. Electricity markets are either monopolistic or competitive. Traditionally, state and local monopolies have dominated the electrical power industry, using price regulations to promote economically efficient behavior. In regulation, it is the regulator who determines the prices.

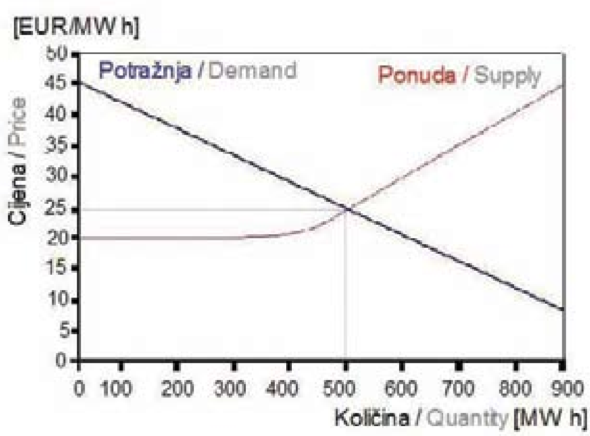
2.2 Market mechanism

The simplest method for describing market interactions among customers and vendors is to assume the existence of an auction. Hypothetically, the auctioneer does the following:

— announces the range of prices to customers and vendors, requiring the market participants to disclose the amount they are prepared to purchase or sell at each price offered and
— determines a price that equalizes the quantity of customer demand with the quantity that the vendors are offering.

Naturally, the majority of markets function without a precisely specified auctioneer. However, in many electrical power systems with separated activities, an independent market operator functions as an auctioneer.

The amount of the demand at each specified price is the demand schedule or, simply, the demand. The amount that is offered at each price is the supply schedule or, simply, the supply. Supply and demand are presented in the graph in Figure 1. The price is shown on the vertical axis (y) and the quantity on the horizontal axis (x). For example, in order to present the electricity market, the vertical axis presents the price per megawatt hour [MWh] and the horizontal axis presents the quantity in MWh.



Slika 1 — Ponuda i potražnja električne energije [1]
Figure 1 – Electricity supply and demand [1]

Na gotovo svim tržištima je vidljivo da kod pada cijena raste potražnja količine. Kupci žele kupiti više po nižoj cijeni, a manje po višoj cijeni. Zato krivulja potražnje bilježi pad. Na većini tržišta se vidi da kako pada cijena, pada i količina koja se nudi. Prema tome, krivulja ponude je pozitivna. Krivulja ponude može biti na nuli ako su opskrbljivači u mogućnosti, zbog svojih troškova, ponuditi više proizvoda za isti trošak.

Razlikuju se promjene u potraživanoj količini zbog promjena u cijeni i pomake u potražnji. Potražnja za električnom energijom može se mijenjati iz sata u sat tijekom dana i iz jednog godišnjeg doba u drugo. Također, krivulja ponude može se mijenjati zbog promjene troškova. Tržišna cijena i količina su u ravnoteži neko vrijeme ako su kupci i prodavači zadovoljni rezultatima tržišta.

2.3 Elastičnost

Da bi se odredila proizvodnja potrebno je prvo odrediti potražnju, odnosno funkciju potražnje za električnom energijom.

Intenzitet promjene količine nabave neke robe na tržištu od strane potrošača zavisno od promjene cijene robe naziva se cjenovna elestičnost potražnje [2]. Elastičnost potražnje se manifestira kao: direktna cjenovna, unakrsna i dohodovna. Isto tako kao što reagira potražnja na promjenu cijene robe, reagira i ponuda, pa se govori o elastičnosit ponude. Elastičnost se izračunava kao odnos između nastale postotne promjene u opsegu potraživane ili ponuđene količine robe i postotne promjene njene cijene.

Zbog toga što se i potraživana količina (Q_d) i ponuđena količina (Q_s) mijenjaju s promjenom cijene, svim je sudionicima na tržištu (uključujući regulatore) bolje ako znaju kako se te količine mijenjaju kod promjene cijene. Reagiranje količine na promjene u cijeni je elastičnost cijena. Regulatori moraju znati kako tržišne količine reagiraju na promjene u cijeni, jer oni određuju cijene kako bi postigli ukupni ciljani prihod. Ako je određena cijena previsoka ili preniska, prihodi će biti manji od očekivanih. Pogrešna je pretpostavka da će se dizanjem cijena nužno povećati i ukupni prihod. Ukupni prihod ovisi o elastičnosti cijene.

Potraživana količina (Q_d) u negativnom je odnosu prema cijeni (kad cijena raste, potražnja pada), pa je elastičnost potražnje negativna.

Kako bi bilo određenije:

On nearly all markets, it is evident that when the price decreases, there is an increase in the quantity of the demand. Customers want to buy more at a low price and less at a high price. Therefore, the demand curve registers a decline. On the majority of markets, it is evident that when the price decreases, the quantity offered also decreases. Accordingly, the supply curve is positive. The supply curve can be at zero if the suppliers are able, due to their costs, to offer more of the product at the same cost.

Changes in the quantity of the demand occur due to changes in the price and shifts in demand. Electricity demand can change from hour to hour during the course of a day and from one season to another. Furthermore, the supply curve can change due to changes in costs. Market prices and quantities are in equilibrium for a time if the customers and vendors are satisfied with the market results.

2.3 Elasticity

In order to determine production, it is first necessary to determine demand, i.e. the function of the demand for electricity.

The intensity of the change in the quantity of the procurement of some goods on the market on the side of the customers, depending upon changes in the prices of goods, is called the price elasticity of demand [2]. The elasticity of demand is manifested as direct price, cross and income elasticity. Similarly, as demand reacts to a change in the price of a good, supply also reacts, so the elasticity of supply is also spoken of. Elasticity is calculated as the ratio between the percentile change in the range of the supply or demand of a quantity of a good and the percentile change in its price.

Therefore, since the quantity demanded (Q_d) and the quantity supplied (Q_s) change with a change in price, it is better for all the market participants (including regulators) if they know how these quantities will change when there is a change in price. The reaction of quantities to changes in price is price elasticity. Regulators must know how market quantities react to changes in price because they determine the prices in order to achieve the total target revenues. If a specific price is too high or too low, revenues will be less than anticipated. It is incorrect to assume that raising prices necessarily increases total revenues as well. Total revenues depend upon price elasticity.

The demanded quantity (Q_d) is in a negative relation to the price (when the price rises, demand falls), so that the elasticity of demand is negative.

More specifically,

$$E_d = \frac{\Delta Q_d}{\Delta P}\frac{[\%]}{[\%]} = \frac{\frac{\Delta Q_d}{Q_d}}{\frac{\Delta P}{P}} = \frac{\Delta Q_d}{\Delta P}\cdot\frac{P}{Q_d} \quad , \tag{1}$$

gdje Δ predstavlja mali porast u količini ili cijeni.

Ako Q_d ne reagira na cijenu (kupuje se ista količina bez obzira na male poraste ili padove cijene), tada je elastičnost potražnje ravna nuli ili potpuno neelastična u Q_d. Ako Q_d dođe na nulu s bilo kakvim porastom cijene, tada je elastičnost potražnje beskonačna ili potpuno elastična.

S druge strane, zbog toga što ponuđena količina (Q_s) raste s porastom cijene, elastičnost ponude je obično pozitivna. Ako je promjena u Q_s mala, ponuda je neelastična. Ako je promjena u Q_s velika, ponuda je elastična.

Naravno, elastičnost i potražnje i ponude ovise o početnoj cijeni. Kod visoke cijene u ravnoteži, potražnja može biti elastična, a ponuda može biti neelastična zbog toga što:

— mali padovi u cijeni mogu navesti više potrošača da uđu na tržište, ali
— proizvođači mogu proizvoditi najviše što mogu bez ulaganja u nove kapacitete, pa je promjena u ponudi mala.

Međutim, kod niske cijene u ravnoteži, potražnja može biti neelastična, a ponuda elastična, jer mali padovi u cijeni neće potaknuti mnogo veću potrošnju, ali mogu dovesti do značajne reakcije u ponudi.

Reagiranje se mijenja i kroz vrijeme. Vremenski pomak znatno smanjuje signifikantnost veze između cijene i opsega potražnje i ponude električne energije. Kako se potrošači navikavaju na više cijene, tako njihovo reagiranje može biti elastičnije. Iznenadni porast cijene električne energije bi potrošače mogao ostaviti s malo alternativa. No, s vremenom se mogu prebaciti, na primjer, na učinkovitije električne uređaje. Nadalje, iznenadni porast cijene električne energije bi mogao dovesti do slabog reagiranja ponude od strane proizvođača električne energije, ali s vremenom bi se mogla ostvariti nova ulaganja u proizvodne kapacitete.

Još jedan razlog za promjenu reagiranja kroz vrijeme je promjena dohotka potrošača. Kako dohodak potrošača raste tako potrošači mijen-

where Δ represents a small increase in quantity or price.

If Q_d does not react to the price (the same quantity is purchased regardless of a small increase or decrease in price), then the elasticity of demand equals zero or is completely inelastic in Q_d. If Q_d reaches zero with any price increase at all, then the elasticity of demand is infinite or perfectly elastic.

From the other side, since the quantity supplied (Q_s) increases with an increase in price, the elasticity of the supply is usually positive. If the change in Q_s is small, the supply is not elastic. If the change in Q_s is large, the supply is elastic.

Naturally, the elasticity of both supply and demand depends upon the initial price. In the case of high prices in equilibrium, demand can be elastic and supply can be inelastic, for the following reasons:

— small price decreases can lure more customers to enter the market,
— however, producers can already be producing the maximum possible without investment in new generating capacity, so that the change in supply is small.

Nevertheless, when low prices are in equilibrium, demand can be inelastic and supply can be elastic because small decreases in price will not stimulate much higher consumption but could lead to significant reactions in supply.

Reaction also changes over time. A temporal shift significantly reduces the significance of the connection among price, the volume of the supply and the demand for electricity. As customers become accustomed to higher prices, their reaction can become more elastic. A sudden price increase in electricity could leave customers with little alternative. However, with time they can switch over, for example, to more efficient electrical devices. Furthermore, a sudden increase in the price of electrical energy could lead to a poor reaction in supply by the electricity producers, but with time new investment could be realized in generating capacity.

One more reason for a change in reaction over time is change in customer income. When customer income increases, customers change consumption jaju uzorke potrošnje. Taj tip reagiranja se naziva dohodovna elastičnost potražnje.

Također, promjene u cijeni zamjenskih sredstava (npr., u nekim slučajevima prirodni plin je zamjena za električnu energiju) ili komplementarnih sredstava (npr., uređaji koji koriste električnu energiju) mogu promijeniti potražnju za električnom energijom. Taj tip reagiranja naziva se unakrsna elastičnost potražnje. Što je reagiranje potražnje na druge cijene veće, to je veća unakrsna elastičnost. Rast cijena zamjenskih sredstava obično vodi do povećanja u potražnji električne energije. Ako cijena prirodnog plina raste, potrošači će radije upotrebljavati relativno jeftiniju električnu energiju. Tu su električna energija i prirodni plin zamjenjiva sredstva. Padovi cijene komplementarnih sredstava mogu dovesti do porasta u potražnji električne energije, pa je unakrsna elastičnost potražnje negativna.

Elastičnost potražnje električne energije vrlo je mala iz dva razloga:

— u jednom dijelu njenu potrošnju uopće nije moguće zbog tehnoloških postupaka supstituirati drugim vidovima energije,
— u drugom dijelu potrošnje upotrebne prednosti električne energije su toliko velike da nju i u tom dijelu potrošnje treba smatrati monopolnim dobrom.

Potražnja za električnom energijom nije stalna, već se neprestano mijenja. Velik broj potrošača konstantno se uključuje, odnosno isključuje iz procesa potrošnje električne energije. Ipak, iskustvo ukazuje na izvjesne pravilnosti u načinu potrošnje električne energije, tako da se može govoriti o satnim, dnevnim, mjesečnim i godišnjim, odnosno sezonskim varijacijama potrošnje električne energije. Varijacije tijekom dana i godine su izrazite, tijekom tjedna manje, a tijekom mjeseca najmanje.

Potražnja za električnom energijom može se formirati i pod jakim utjecajem ekonomske politike. To se u prvom redu odnosi na različite oblike subvencioniranja pojedinih kategorija potrošača.

Poznavanje karakteristika potražnje za električnom energijom od vitalnog je značenja za vođenje optimalne politike cijena električne energije, jer struktura potražnje ima presudan utjecaj na strukturu tarifnog sustava, čiji je zadatak da što vjernije prenese troškove na one potrošače koji su ih i uzrokovali.

Iz navedenog proizlazi da se veličina i karakteristike buduće potražnje električne energije ne mogu predvidjeti s potpunom sigurnošću.

patterns. This type of reaction is called the income elasticity of demand.

Furthermore, changes in the price of replacement energy sources (for example, in some cases natural gas can serve as a replacement for electricity) or complementary devices (for example, devices that use electricity) can change demand for electricity. This type of reaction is called the cross elasticity of demand. The greater the reaction of demand to other prices, the greater the cross elasticity. An increase in the price of replacement energy sources usually leads to an increase in the demand for electricity. If the price of natural gas rises, customers will prefer to use relatively inexpensive electricity. Here, electricity and natural gas are interchangeable energy sources. A decrease in the prices of complementary energy sources can lead to an increase in the demand for electricity, so that the cross elasticity of demand is negative.

The elasticity of the demand for electricity is very low for two reasons:

— in one part of consumption, elasticity is not possible at all due to the technological procedures for the substitution of other forms of energy,
— in another part of consumption, the advantages of using electricity are so great that it should also be considered as a monopoly commodity here.

The demand for electricity is not steady but changes constantly. A large number of customers are constantly being connected or disconnected from the process of the consumption of electricity. Nonetheless, experience has demonstrated that there are certain regularities in the manner of consuming electricity, so that it is possible to speak of hourly, daily, monthly, yearly and seasonal variations in the consumption of electricity. Variations during a day or year are marked, less during a week and the least during a month.

The demand for electricity can also be formed under the powerful influence of economic policy. In the first place, this refers to various forms of subsidies for individual categories of customers.

Familiarity with the characteristics of demand for electricity is of vital significance for conducting optimal electricity price policy because the demand structure has a crucial impact upon the structure of the tariff system, the task of which is to transfer costs to those customers who are responsible for incurring them in the most accurate manner.

Therefore, it follows that the quantity and characteristics of future electricity consumption cannot be foreseen with complete certainty.

2.4 Zašto restrukturirati i deregulirati?

Najčešći argumenat u korist deregulacije je neučinkovitost regulacije. Neučinkovitost regulacije je neosporna, ali iz toga ne proizlazi da će deregulacija biti nužno bolja, jer tržišta električne energije imaju svojih vlastitih neučinkovitosti koje se trebaju usporediti s neučinkovitostima regulacije. Do danas su takve usporedbe, većim dijelom, bile spekulativne.

Najodlučniji odgovori su najčešće utemeljeni na malom broju informacija. Jedni tvrde da je regulacija nužna zato jer je električna energija osnovna potreba. A što je sa stanovanjem? Ta je potreba još osnovnija, a stanogradnja je gotovo 100 % deregulirana. Drugi tvrde da konkurencija omogućava poticaje koji snizuju troškove, dok to kod regulacije nije slučaj. A, što je s mnogim reguliranim tvrtkama koje pouzdano proizvode električnu energiju već mnogo godina za manje od 6 USDc/kWh? Nedostaju li njima poticaji za smanjivanje troškova [3]?

Elektroenergetski sektor je zbog svojih tehnoloških karakteristika smatran i tretiran kao prirodni monopol. Karakteristika je prirodnih monopola da mogu ponuditi nižu cijenu od konkurencijskog tržišta. Nedostatak prirodnog monopola je preduvjet uspješne deregulacije. Jedan popularni argument u korist deregulacije glasi da je tehnički napredak u posljednje vrijeme izbrisao uvjete za prirodni monopol u proizvodnji. Ovo mišljenje pretpostavlja da je prethodno proizvodnja bila prirodni monopol, jer se najučinkovitija elektrana veličinom približavala 1 000 MW, a nove tehnologije su elektranu od 100 MW učinile gotovo jednako učinkovitom. Ali ipak, nitko tko smatra da su male učinkovite elektrane nužan uvjet za konkurenciju ne čini se zabrinut zbog prisustva velikih opskrbljivača na novim tržištima [3].

Regulacija ima dva osnovna problema:

- ne može ostvariti jaki poticaj za opskrbljivače tako jeftino kao konkurencijsko tržište,
- ni sama regulacijska tijela nemaju prave poticaje. Dobro obučeni regulatori bi mogli ostvariti puno bolju regulaciju. Ali da bi vlada omogućila kompetentnu regulaciju, politički proces bi se trebao promijeniti.

Prava konkurencijska tržišta rade dvije stvari odjednom. Omogućuju snažne poticaje:

- za održavanje cijene blizu granice marginalnog troška i
- za minimalizaciju troška.

2.4 Why restructure and deregulate?

The most common argument in support of deregulation is the inefficiency of regulation. The inefficiency of regulation is indisputable but it does not follow that deregulation will necessarily be better. This is because electricity markets have their own inefficiencies, which should be compared with the inefficiencies of regulation. Heretofore, such comparisons have been largely speculative.

The most decisive responses are most frequently based upon limited information. Some assert that regulation is necessary because electricity is a basic need. What about housing? This need is even more basic and housing construction is nearly 100 % deregulated. Others assert that competition provides incentives that reduce costs, while this is not the case with regulation. What about the many regulated companies that reliably produce electricity for many years for less than 6 USc/kWh? Do they lack incentive to reduce costs [3]?

The electrical power sector, due to its technological characteristics, is considered to be and treated like a natural monopoly. A characteristic of natural monopolies is that they can offer a lower price than competitive markets. A shortcoming of a natural monopoly is the prerequisite of successful deregulation. One popular argument in favor of deregulation is that technical progress in recent times has eliminated the prerequisites for a natural monopoly in production. Such a position assumes that in the past production had a natural monopoly because the greatest efficiency could only be obtained from an electrical power plant that produced close to 1 000 MW, while with new technologies power plants producing 100 MW are nearly as efficient. However, no one who is of the opinion that small efficient power plants are a necessary prerequisite for competition seems to be worried due to the presence of large suppliers on the new markets [3].

Regulation has two basic problems:

- it cannot achieve strong incentives for suppliers as inexpensively as competitive markets,
- not even the regulatory bodies have genuine incentives. Well-trained regulators could achieve much better regulation but if the government were to make competent regulation possible, the political process would also have to be changed.

Genuine market competition does two things at the same time, providing powerful incentives for the following:

- maintaining prices near the limits of marginal costs and
- minimizing costs.

Regulacija može ostvariti ili jedno ili dugo, ali ne oboje. Mora činiti ustupke jer opskrbljivači uvijek poznaju tržište bolje od regulatora. Ustupci su srž suvremene teorije regulacije.

Regulacija se može poboljšati ako se unaprijedi praktično znanje regulatora. Ako regulator raspolaže s relativno velikom količinom informacija, ustupak može biti zadovoljavajući, ali nikad neće biti dobar kao savršena konkurencija. Konkurencija može održati prosječnu cijenu na razini dugoročnih troškova i u isto vrijeme vršiti maksimalni pritisak na minimalizaciju troškova. U najboljem slučaju, regulacija će sve pristojno odraditi u oba slučaja, ali u nijednom tako dobro kao konkurencija.

U praksi regulacija je sklona griješiti u smislu snižavanja cijena prema troškovima proizvodnje. Činjenica je da većina regulatora vjeruje da im je to jedini posao i, da to mogu, uveli bi čistu regulaciju troškova usluge. Na sreću, jednostavno previše je zamorno stalno prepravljati tarife, pa se sve otprilike svodi na limit koji se mijenja otprilike svake tri godine. Taj nenamjerni regulatorski zastoj glavni je faktor koji omogućava regulaciji troškova usluge da ostvari bar neke poticaje. Omogućuje određene poticaje za minimalizaciju troškova, ali oni su slabiji od onih koji bi bili ostvareni optimalnim ustupkom. No, čak i to je premalo po standardima konkurencijskog tržišta.

Zbog činjenice da je poduzećima bilo dozvoljeno prenošenje troškova na potrošače kroz regulirane tarife, postojalo je malo poticaja za smanjenje troškova ili investiranja s pravilnim razmatranjem rizika. U tako reguliranom okviru, tvrtke su maksimalizirale dobit, koja je ipak bila podvrgnuta regulacijskim ograničenjima.

Kod savršene konkurencije, teoretski, interakcija mnogobrojnih kupaca i prodavača ostvaruje tržišnu cijenu koja je jednaka trošku proizvodnje zadnje prodane jedinice. To je ekonomski učinkovito rješenje. Cilj deregulacije je strukturiranje konkurencijskog tržišta s dovoljnim brojem proizvođača kako bi se eliminirala tržišna moć, odnosno sposobnost tvrtke ili grupe tvrtki da određuju cijene veće od troškova proizvodnje.

Kod deregulacije, elektroenergetska poduzeća moraju razdvojiti regulirane od dereguliranih aktivnosti i natjecati se s novim tvrtkama koje se pojavljuju na tržištu. Ekonomski mehanizam donošenja odluka kod konkurencije odgovara decentraliziranom procesu u kojem svaki sudionik maksimalizira dobit koja je jednaka razlici između ukupnog prihoda i ukupnih troškova. Međutim, kod konkurencije, vraćanje investicije u novi posao nije zajamčeno. Stoga, procjena

Regulation can achieve one or the other but not both. It must make concessions because the suppliers always know the market better than the regulators. Concessions are the essence of contemporary regulation theory.

Regulation can be improved if the practical knowledge of the regulators is improved. If a regulator has a relatively large amount of information at his disposal, a concession may be satisfactory but it will never be as good as perfect competition. Competition can maintain an average price at the level of long-term costs while at the same time exert maximum pressure on minimizing costs. In the best case, regulation will do everything properly in both cases but in neither case as well as competition.

In practice, regulation tends to err in the sense of lowering prices according to production costs. It is a fact that the majority of regulators believe that this is their only job and if they could they would introduce the complete regulation of service costs. Fortunately, it is simply too tedious to adjust tariffs constantly. Therefore, all of this is reduced to a limit that changes approximately every three years. This unintentional regulatory glitch is the main factor that makes it possible for the regulation of the costs of services to provide at least some incentives for minimizing costs but they are weaker than those that would be achieved by an optimal concession. However, even those would be too little according to the standards of the competitive market.

Due to the fact that companies were permitted to pass on costs to customers through regulated tariffs, there was little incentive for reducing expenditures or investment with proper risk assessment. Within such a regulatory framework, companies maximized profit, which was nevertheless subject to regulatory limits.

In the case of perfect competition, theoretically the interaction of many customers and vendors creates a market price that is equal to the cost of the production of the last unit sold. This is an economically efficient solution. The goal of deregulation is the structuring of a competitive market with a sufficient number of customers in order to eliminate market power, i.e. the ability of companies or groups of companies to determine prices higher than production costs.

With deregulation, electrical power companies must unbundle regulated and deregulated activities and compete with the new companies that appear on the market. The economic mechanism of decision making under competition corresponds to a decentralized process in which each participant maximizes profit that is equal to the difference between total revenues and total costs. However, with competition, the return of an investment in a new job is not guaranteed. Therefore, risk rizika postaje ključni dio u industriji električne energije.

Još jedan cilj kojem teži deregulacija izbjegavanje je unakrsne novčane potpore među različitim potrošačkim razredima ostvarivanjem transparentnijih tarifa. Električna energija se kupuje na tržištu po postavljenim cijenama, dok se regulirani troškovi (npr. za uslugu prijenosa) naplaćuju po odvojenom sistemu kroz pristupne tarife.

Krajnji cilj je postizanje tehnički pouzdane i ekonomski učinkovite industrije električne energije. Na tom putu stoje mnogi organizacijski, institucijski i regulacijski problemi koji se moraju riješiti deregulacijom.

3 RAZVOJ TRŽIŠTA ELEKTRIČNE ENERGIJE

3.1 Od monopola do tržišta

Nakon 2. svjetskog rata u mnogim je zemljama, prvenstveno zbog strateških razloga, elektroenergetski sektor nacionaliziran i u pravilu organiziran u jedno vertikalno integrirano poduzeće, koje je bilo jedini opskrbljivač električnom energijom na svom operativnom teritoriju i imalo je dužnost opskrbljivati električnom energijom sve potrošače na tom teritoriju. Ta je situacija bila uobičajena u Europi i Latinskoj Americi. Elektroenergetski sustavi razvijali su se prema specifičnim uvjetima pojedinih država, što je dovelo do značajnih razlika među njima, u strukturi i izgrađenosti kapaciteta, u strukturi i razini cijena električne energije i u organizaciji i vlasništvu. Posebno su bile velike razlike između elektroenergetskih sustava razvijenih zapadnih zemalja i elektroenergetskih sustava istočnoeuropskih zemalja, danas poznatijih pod nazivom tranzicijske zemlje.

Elektroenergetske tvrke bile su većinom u vlasništvu države, regionalne, odnosno lokalne vlasti, ali i u privatnom vlasništvu i u vlasništvu udruženja potrošača.

Od početka 1980-ih do danas elektroenergetski sektor u cijelom svijetu podvrgnut je značajnim reformama koje karakterizira:

— restrukturiranje vertikalno integrirane monopolističke organizacije u konkurentna poduzeća,
— otvatranje tržišta u proizvodnji i opskrbi,
— privatizacija državnog vlasništva.

Restrukturiranje znači pripremu za liberizaciju tržišta električne energije i privatizaciju, odno-

assessment becomes a crucial part of the electrical power industry.

One more goal to which deregulation aspires is avoiding cross financial supports among various classes of customers achieved by more transparent tariffs. Electricity is purchased on the market according to the set prices, while regulated costs (for example, for the service of transmission) are collected according to a separate system through access tariffs.

The ultimate goal is the achievement of a technically reliable and economically efficient electrical power industry. On the path, there are many organizational, institutional and regulatory problems that must be resolved through deregulation.

3 THE DEVELOPMENT OF THE ELECTRICITY MARKET

3.1 From monopoly to market

Following World War II, the electrical power sector was nationalized in many countries, primarily due to strategic reasons. As a rule, it was organized into a vertically integrated company which was the sole supplier of electricity on its operative territory and had the task of supplying electricity to all the customers within its territory. This was the customary situation in Europe and Latin America. Electrical power systems developed according to the specific conditions of the individual countries, which led to significant differences among them in the structure and developed capacities, the structure and the level of electricity prices, and organization and ownership. There were especially considerable differences between the electrical power systems of developed Western countries and the electrical power systems of Eastern European countries, today known as countries in transition.

The majority of electrical power companies were owned by the state, regional or local authorities, but could also be under private ownership and under the ownership of customer associations.

From the beginning of the 1980s until the present, the electrical power sector in the world has been subjected to significant reforms, characterized by the following:

— the restructuring of vertically integrated monopolistic organizations into competitive companies,
— the opening of markets in production and supply, and
— the privatization of state property.

Restructuring means preparation for the liberalization of the electricity market and privatization, i.e.

sno reorganizaciju i racionalizaciju s ciljem povećanja efikasnosti poslovanja.

Otvaranje elektroenergetskog tržišta znači deregulaciju i demonopolizaciju, odnosno konkurenciju u proizvodnji i opskrbi.

Najznačajniji faktori koji potiču reformu industrije električne energije diljem svijeta su:

— nove proizvodne tehnologije, kao što su plinske turbine s kombiniranim ciklusom (CCGT), smanjile optimalnu veličinu električnih generatora,
— globalna konkurencijska ekonomija traži smanjenje ulaznih troškova, a električna energija je trošak u svim industrijama, a u mnogima i značajan,
— država, kao vlasnik i upravljač tradicionalnih industrija ne može odgovoriti na ekonomske i tehnološke promjene toliko brzo kao privatni vlasnici, pa zbog toga potiče privatizaciju,
— informacijske tehnologije i komunikacijski sustavi omogućuju razmjenu velike količine infomacija, potrebnih za upravljanje tržištem električne energije,
— globalizacijski procesi koji teže okrupnjavanju kapitala,
— razvoj tehnologije za prijenos električne energije stvorio je nove mogućnosti za razvoj tržišta električne energije i konkurencije.

CCGT proizvođači natječu se kako bi ostvarili tehničku učinkovitost do 60 %, kratki rok izgradnje elektrane (manje od dvije godine), i niske troškove ulaganja (oko 500 USD/kW). Takav tehnički razvitak, uz niske cijene prirodnog plina i nove mreže za njegov transport, učinili su ovu tehnologiju dominatnim izborom za nove investicije na konkurencijskim tržištima proizvodnje električne energije.

Globalna konkurencija koju potiču međunarodne tvrtke naglašava međunarodno uspoređivanje cijena, što potiče države da smanje troškove električne energije kako bi bile globalno konkurentne. Procese restrukturiranja i deregulacije provode vlade uvođenjem tržišta električne energije s ciljem povećanja učinkovitosti i smanjenja cijena. Vlade potiču razvoj tržišta i otvaranjem tržišta konkurenciji iz susjednih zemalja s nižim troškovima s ciljem smanjenja cijena.

Državno vlasništvo je u zadnjem desetljeću bilo u krizi zbog više razloga. Npr., u Latinskoj Americi u državama koje su imale visoku potrošnju električne energije bila su nužna znatna ulaganja, a država s velikim vanjskim dugom nije bila u stanju provesti potrebna ulaganja u proizvodnju. Ta je situacija, uz preporuke međunarodnih

reorganization and rationalization with the goal of increasing the efficiency of operations.

Opening of the electricity market means deregulation and demonopolization, i.e. competition in production and supply.

The most significant factors that promote electricity reform throughout the world are as follows:

— new production technologies, such as combined cycle gas turbines (CCGT), have reduced the optimal size of a power generator,
— the global competition of the economy requires a reduction in input costs. Electricity is an expense in all industries, which is significant in many,
— the state, as the owner and manager of traditional industries, cannot respond to the economic and technological changes as quickly as private owners and, therefore, promotes privatization,
— information technologies and communication systems make the exchange of the large quantities of information necessary for the management of the electricity market possible,
— the globalization process favors the consolidation of capital,
— the development of technology for the transmission of electricity has created new possibilities for the development of the electricity market and competition.

CCGT producers compete in order to achieve up to 60 % technical efficiency, power plant construction within a short period of time (less than two years) and low investment costs (approximately 500 USD/kW). Such technical development, together with the low prices of natural gas and new transport networks, have made this technology the dominant choice for new investment on competitive electricity production markets.

The global competition promoted by international companies emphasizes international price comparisons, providing incentives for states to reduce electricity costs in order to be globally competitive. The processes of restructuring and deregulation are implemented by governments through the introduction of electricity markets, with the goal of increasing efficiency and lowering prices. Governments promote market development and the opening of markets to competition from neighboring countries with lower costs in order to achieve the goal of lowering prices.

State ownership has been in crisis during the past decade for several reasons. For example, in Latin American countries which had high electricity consumption, significant investments were necessary and a country with a large foreign debt was not in a position to implement the necessary investment in production. This situation, with the recommendations of the international financial financijskih institucija, kao što su Svjetska banka i Interamerička banka za razvoj, dovela do toga da vlasti potaknu privatizaciju i restrukturiranje. Također, internacionalizacija tržišta goriva dovela je u pitanje državne poticaje za određene primarne izvore energije.

Informacijske tehnologije i komunikacijski sustavi omogućuju napredna i on-line tržišta elektične eneregije s više sudionika i više tipova transakcija. Nadalje, mjerenje, naplaćivanje, kontrola kvalitete i načini kontrole napona, koji se temelje na novim informacijskim tehnologijama i komunikacijskim sustavima su ono što se nudi kod restrukturiranja i deregulacije.

Deregulaciju su poticale i cijene više, od onih u susjednim državama i regijama. Na područjima s visokim cijenama, potrošači i vlade su, pod utjecajem vala deregulacije, zagovarali restrukturiranje.

S ciljem ublažavanja problema i razlika u energetskom sektoru, odnosno brže prilagodbe globalizacijskom trendu, u prosincu 1991. godine u Haagu je potpisana Europska energetska povelja od strane 49 europskih zemalja, SAD-a, Kanade, Japana i Australije. Kako Povelja kao politički dokumenat nije imala provedbenu snagu, u prosincu 1994. godine u Lisabonu potpisan je Ugovor o europskoj energetskoj povelji, potpisnik kojeg je i Hrvatska**.** Poveljom se potiče razvoj trgovine u energetici**,** suradnja na području energetike, energetska efikasnost i zaštita okoliša.

Kroz restrukturiranje i deregulaciju, pravno su i funkcionalno razdvojena vertikalno integrirana poduzeća. Uvedena je konkurencija u veleprodaju i maloprodaju električne energije. Veleprodajna tržišta električne energije čini nekoliko proizvodnih tvrtki koje se natječu u prodaji svoje električne energije kroz središnji pool ili preko dvostranih ugovora s kupcima. Uvedena je i maloprodajna konkurencija koja kupcima omogućava da odaberu jednog između više prodavača ili da kupuju direktno s veleprodajnog tržišta.

Pionir u reformi elektroenergetskog sektora bio je Čile razvojem konkurencijskog sustava za proizvodnju električne energije utemeljenu na marginalnim cijenama u ranim 1980.-im godinama. Početkom 1990-ih slijedila ga je Argentina koja je 1992. godine privatizirala neučinkoviti sektor električne energije u državnom vlasništvu podijelivši ga na proizvođače, prijenosnike i distributere, uz uvođenje konkurencijskog proizvodnog tržišta. Ta su iskustva primijenjena u ostalim zemljama Latinske Amerike, kao što su Bolivija, Peru, Kolumbija, Gvatemala, El Salvador, Panama i djelomično u Brazilu i Meksiku.

institutions such as the World Bank and the Inter-American Development Bank, led to the authorities promoting privatization and restructuring. Furthermore, the internationalization of the fuel market called state incentives for certain primary sources of energy into question.

Information technologies and communication systems also make it possible to have advanced and on-line electricity markets with many participants and types of transactions. Furthermore, metering, collection, quality control and voltage control methods, based upon the new information technologies and communication systems, are offered in restructuring and deregulation.

High prices in comparison to those in neighboring countries and regions also provided an incentive for deregulation. . In areas with high prices, customers and governments urged restructuring under the influence of a wave of deregulation.

With the goal of addressing the problem and differences in the energy sector, i.e. more rapid adaptation to the globalization trend, in December 1991 the European Energy Charter was signed at The Hague by forty-nine European countries, the United States, Canada, Japan and Australia. Since the charter as a political document lacked powers for its implementation, in December 1994 the European Energy Charter Treaty was signed in Lisbon, with Croatia among the signers. The treaty promotes the development of commerce in energetics, cooperation in the area of energetics, energy efficiency and environmental protection.

Through restructuring and deregulation, vertically integrated enterprises were unbundled, both legally and functionally. Competition in the wholesale and retail of electricity was introduced. The wholesale electricity market consists of several production companies that compete in the sale of their electricity through a central pool or via bilateral contracts with customers. Retail competition has also been introduced that makes it possible for customers to choose one of several vendors or to purchase directly on the wholesale market.

A pioneer in the reform of the electrical power sector was Chile, with the development of a competitive system for the production of electricity based upon marginal prices in the early 1980s. At the beginning of the 1990s, it was followed by Argentina, which in 1992 privatized the inefficient electrical power sector that had been under state ownership, dividing it into production, transmission and distribution, with the introduction of a competitive production market. These experiences were applied in other countries in Latin America, such as Bolivia, Peru, Columbia, Guatemala, El Salvador, Panama and partially in Brazil and Mexico.

U nekim saveznim državama SAD-a, u Australiji, na Novom Zelendu, i u nekim provincijama u Kanadi deregulacija industrije električne energije je uvedena kao način povećanja učinkovitosti i sniženja cijena [1].

Skandinavske zemlje, slijedeći Norvešku, postupno su stvorile nordijsko veleprodajno tržište električne energije.

3.2 Dobrobiti konkurencijskih veleprodajnih tržišta

Konkurencija u elektroenergetskoj djelatnosti odnosi se na dvije razine: konkurencija u veleprodaji i konkurencija u maloprodaji. Veleprodaja se odnosi na prodaju električne energije koju prodaju elektrane. One svoju energiju prodaju na veliko, velikim potrošačima i opskrbljivačima.

Jedan od glavnih ciljeva deregulacije je postizanje učinkovito konkurencijskog veleprodajnog tržišta. Konkurencija omogućava mnogo snažnije poticaje za smanjenje troškova nego što to čini tipična regulacija troškova usluge, te dovodi do toga da opskrbljivači brže uvode razne vrste inovacija kojima se smanjuju troškovi. One uključuju mudrije investiranje, jeftiniju izgradnju novih kapaciteta, učinkovitije održavanje i manje troškove rada.

Druga prednost konkurencije je njena sposobnost da zadrži cijenu na razini najnižeg troška. Ovo je manja prednost samo zbog toga što je tradicionalna regulacija naglašavala ovu stranu regulatorskog procesa. Još uvijek minimalizacija troškova može biti značajna prednost. Kogeneracija opet može poslužiti kao primjer. Nakon što su je regulatori odlučili poticati, trebala im je cijena te udruženo proizvedene energije. Stvorena je formula s ciljem oponašanja tržišne cijene. Naravno da su političke snage intervenirale, a rezultat su bili dugogodišnji ugovori s vrlo visokim cijenama [4]. Oni su doveli do, vjerojatno i presnažnog, poticaja za udruženu proizvodnju. Konkurencijsko tržište može u isto vrijeme ostvariti i prave poticaje i prave cijene.

U početku su se veleprodajna tržišta kreirala za ekonomično otpremanje proizvedenih količina u središnji pool, kojim je upravljao operator sustava. Sudjelovanje u poolu je bilo obvezno za sve proizvođače. Tako je bilo u Argentini, Čileu, Engleskoj i Walesu [5].

Veleprodajna tržišta imaju veliku nestalnost cijena zbog dnevnih i sezonskih promjena u opskrbi i potražnji. To uzrokuje dva važna problema kod deregulacije vezana za reagiranje potražnje na promjene cijena i nova ulaganja u proizvodne resurse.

In some states of the USA, Australia, New Zealand and some provinces in Canada, deregulation of the electrical power industry was introduced as a means for increasing efficiency and lowering prices [1].

Scandinavian countries, following Norway, gradually created the Nord Pool wholesale electricity market.

3.2 Benefits of competitive wholesale markets

Competition in electricity operations refers to two levels: competition in wholesale and competition in retail. Wholesale refers to the sale of electricity by power plants. They sell their energy wholesale to large customers and suppliers.

One of the chief goals of deregulation is to achieve effective competition on the wholesale market. Competition makes much more powerful incentives possible for reducing costs than the typical regulation of service costs, and results in suppliers introducing various types of innovations more quickly, thereby reducing costs. They include wiser investment, less expensive construction of new generating capacity, more efficient maintenance and lower labor costs.

A second advantage of competition is its ability to maintain prices at the level of lowest cost. This is a lesser advantage only because traditional regulation has emphasized this aspect of the regulatory process. Minimizing costs can still be a significant advantage. Cogeneration can serve as an example again. After regulators decided to promote it, they needed a price and pooled energy production. A formula has been created with the goal of modeling market prices. Naturally, political powers intervened and the results were long-term contracts with very high prices [4]. These led to what were most likely excessive incentives for pooled production. A competitive market can achieve correct incentives and correct prices at the same time.

In the beginning, the wholesale markets were created for the economical delivery of the quantities produced to a central pool, administered by the system operator. Participation in the pool was mandatory for all producers. This is how it was in Argentina, Chile, England and Wales [5].

Wholesale markets have great price instability due to daily and seasonal changes in supply and demand. This causes two important problems in deregulation connected with the reaction by demand to changes in prices and new investment in production resources.

Kod regulacije je potražnja za električnom energijom smatrana neelastičnom i novi kapaciteti gradili su se na temelju pretpostavljane potražnje. Kod deregulacije se pretpostavlja da će konkurencijske cijene potaknuti novu proizvodnju.

Čini se da će glavna dobrobit konkurencije doći iz područja potražnje, a ne iz područja ponude. Visoke cijene na veleprodajnom tržištu će se prenijeti na potrošače, barem kod marginalne potrošnje, i zbog toga će potrošači ograničiti svoju potražnju kad je cijena najviša, a proizvodnja najskuplja. To će smanjiti broj proizvođača i smanjiti ukupne troškove proizvodnje električne energije. Konkurencijsko tržište će tu uštedu prenijeti na potrošače.

3.3 Maloprodajna konkurencija i potrošački izbor

Cilj deregulacije je pružiti potrošačima tržišno utemeljene cijene električne energije uz pouzdanu uslugu i učinkovite cijene. Uvođenje potrošačkog izbora razlikuje se od države do države. U Norveškoj su se svi potrošači kvalificirali za odabir svog opskrbljivača kad je krenulo konkurencijsko veleprodajno tržište. U Španjolskoj je regulator primijenio posebne mjere, kao što su smanjenje pristupnih tarifa, kako bi potaknuo izlazak reguliranih potrošača. U većini drugih zemalja prakticirano je progresivno uvođenje uvjeta koji određuju kvalificirane potrošače, počevši od najvećih potrošača i završavajući s kućanstvom.

Dobar pokazatelj zrelosti konkurencije i tržišta je broj učinkovito nereguliranih potrošača i količina ukupne električne energije potrošene izvan reguliranih tarifa.

Međutim, izvješća uglednih stručnjaka na području deregulacije industrije električne energije ukazuju na problem kako dugoročno osigurati pravi tržišni okvir za konkurenciju u maloprodaji električne energije [6]. Misli se na brojne tehničke, regulatorne i praktične uvjete koje je potrebno osigurati kako bi se izbjegle neželjene devijacije i značajni dodatni troškovi.

U nastavku se daje pregled procesa reformi u elektroenergetskom sektoru, odnosno otvaranja tržišta električne energije u Europskoj uniji, tranzicijskim zemljama, SAD-u i Hrvatskoj. Iako je većina tranzicijskih zemalja već u Europskoj uniji, posebno su istaknute zbog specifičnog negativnog naslijeđa iz socijalizma.

Under regulation, the demand for electricity was considered to be inelastic and new generating capacity was constructed on the basis of the assumed demand. Under deregulation, it is assumed that competitive prices will stimulate new production.

It appears that the main benefit of competition will come from the area of demand and not from the area of supply. High prices on the wholesale market will be transferred to customers, at least as marginal costs, and therefore customers will limit their demand when the price is the highest and production is the most expensive. This will reduce the number of producers and reduce the total costs of electricity production. The competitive market will pass on these savings to the customers.

3.3 Retail competition and customer choice

The goal of deregulation is to provide customers with market-based electricity prices with reliable service and effective prices. The introduction of customer choice differs from country to country. In Norway, all customers qualified for choosing their suppliers when the competitive wholesale market started operations. In Spain, the regulator applied special measures, such as reducing access tariffs, in order to provide an incentive for regulated customers to leave. In the majority of other countries, the progressive introduction of conditions was practiced for the determination of qualified customers, starting from the largest customers and ending with households.

A good index of competition and market maturity is the number of effectively unregulated customers and the quantity of the total electricity consumed outside regulated tariffs.

However, reports from distinguished experts in the area of the deregulation of the electrical power industry discuss the problem of how to secure a long-term legal market framework for competition in the retail of electricity [6]. This refers to the numerous technical, regulatory and practical prerequisites that must be secured in order to avoid undesirable deviations and significant added costs.

The next section presents a review of the reform processes in the electrical power sector, i.e. the opening of the electricity markets in the European Union, countries in transition, the United States and Croatia. Although the majority of countries in transition are already in the European Union, they are discussed separatelyowing to their specific negative socialistic legacy.

3.4 Europska unija

3.4.1 Pristup otvaranju tržišta

Prva tržišta električne energije u Europi uspostavljena su početkom 1990-tih godina prošlog stoljeća u Velikoj Britaniji i u skandinavskim zemljama.

I u okviru same Europske unije postojale su velike razlike u pogledu organizacije i vlasništva u elektroenergetskom sektoru. Tako su npr. Francuska, Grčka, Turska, Italija i Portugal nacionalizirale svoje monopole za proizvodnju i prijenos električne energije. U mnogim zemljama elektroprivrede rade kao regionalna poduzeća (Austrija, Nizozemska, Njemačka), a u Belgiji, Danskoj i Španjolskoj proizvodnja je uglavnom u privatnom vlasništvu. Osim regionalnih poduzeća u Njemačkoj postoje i mješovita poduzeća (javno i privatno). Prijenosna mreža je uglavnom nacionalizirana [7].

Takvo stanje rezultiralo je potrebom usklađivanja, ali i uvažavanja određenih posebnosti unutar Europske unije. To je iznjedrilo Direktive Europske unije koje predstavljaju minimum zahtjeva koje je Europska unija postavila pred zemlje članice u cilju ukidanja monopola u elektroenergetskom sektoru i otvaranja tržišta električne energije. Tako se Direktivom 96/92EC, odnosno njenom nasljednicom Direktivom 2003/54/EC, uspostavljaju zajednička pravila za proizvodju, prijenos, distribuciju i opskrbu električnom energijom.

Osnove liberalizacije tržišta električne energije temelje se na uspostavi konkurencije u proizvodnji i opskrbi te u slobodnom pristupu prijenosnoj i distribucijskoj mreži na području Europske unije, s ciljem stvaranja unutarnjeg tržišta električne energije. Da bi se stvorilo učinkovito tržište električne energije potrebno je provesti sedam osnovnih mjera [8]:

— otvaranje tržišta električne energije na strani proizvodnje, što znači omogućavanje izgradnje i upravljanja proizvodnim kapacitetima na tržišnim osnovama,
— osigurati slobodan pristup treće strane. Budući je izgradnja paralelne prijenosne i distribucijske mreže ekonomski neopravdana, nužno je omogućiti pristup trećoj strani postojećim mrežema i to pod jednakim, nediskriminirajućim uvjetima,
— razdvajanje (engl. *unbundling*) djelatnosti prijenosa i distribucije od proizvodnje i opskrbe unutar postojećih vertikalno povezanih poduzeća. Razdvajanje je moguće provesti na četiri načina ili u njihovoj kombinaciji: razdvajanje računovodstva za poduzeće koje se bavi prijenosom ili distribucijom

3.4 The European Union

3.4.1 The approach to opening markets

The first electricity markets in Europe were established at the beginning of the 1990s in Great Britain and the Scandinavian countries.

Within the framework of the European Union, there were great differences regarding organization and ownership in the electrical power sector. Thus, for example, France, Greece, Turkey, Italy and Portugal nationalized their monopolies for the production and transmission of electricity. In many countries, the electrical power industries operate as regional enterprises (Austria, the Netherlands and Germany) and in Belgium, Denmark and Spain production is chiefly under private ownership. In addition to the regional enterprises in Germany, there are also enterprises of mixed ownership (public and private).

The transmission networks are nationalized for the most part [7]. This situation resulted from the need for coordination but also for taking certain specificities into account within the European Union. This resulted in the directives of the European Union that represent the minimum prerequisites that the EU demands of member states, with the goal of eliminating monopolies in the electrical power sector and opening the electricity markets. Thus, according to Directive 96/92/EC, respectively its successor Directive 2003/54/EC, common regulations were established for the production, transmission, distribution and supply of electrical power.

The basic liberalization of the electricity market is based upon the establishment of competition in production and supply, and in free access to the transmission and distribution networks within the territory of the European Union, with the goal of creating an internal electricity market. In order to create an efficient electricity market, it is necessary to implement seven basic measures [8]:

— the opening of the electricity markets on the production side, which means making possible the construction and administration of generating capacities on market foundations,
— the securing of free access by third parties. Since the construction of parallel transmission and distribution networks is economically unjustified, it is necessary to facilitate access by a third party to the existing networks under equal, nondiscriminatory conditions.
— the unbundling of the operations of the transmission and distribution from production and supply within the existing vertically linked enterprises. Unbundling can be implemented in four ways or in combinations thereof:
  · the unbundling of accounting for enterprises engaged in transmission or distribution represents the weakest aspect of unbundling,

predstavlja najslabiji vid razdvajanja,
  · razdvajanje upravljanja na način da se upravljanje mrežom odvoji od upravljanja ostatkom poduzeća,
  · pravno razdvajanje na način da se osnuje posebna pravna osoba čije će se poslovanje ograničiti na mreže,
  · razdvajanje vlasništva na način da se okomito povezano poduzeće obveže na prodaju mreže,
— stvaranje neovisnog regulatornog tijela, jer organiziranje učinkovitog tržišta električne energije zahtijeva učinkovitu regulaciju prijenosnih i distribucijskih mreža iz tri razloga:
  · sprječavanje pretjerano visokih cijena,
  · sprječavanje subvencioniranja i
  · sprječavanje diskriminacije,
— osiguranje visoke razine javnih usluga s ciljem zaštite javnog interesa vezano za sigurnost opskrbe, zaštitu okoliša i zaštitu kupaca,
— reciprocitet pristupa tržištima drugih zemalja, odnosno ujednačenje tempa liberalizacije,
— stvaranje učinkovitih pravila na razini Europske unije.

Stvaranje unutarnjeg tržišta električne energije u Europskoj uniji započelo je Direktivom o tranzitu električne energije putem prijenosnih mreža iz 1990. godine, čiji je glavni cilj bio osigurati da operator mreže u jednoj od zemalja članica ne može ometati razmjenu električne energije između drugih zemalja članica.

Današnje unutarnje tržište električne energije Europske unije zasniva se na Direktivi 96/92/EC [9] od 1996-12-19. Na snagu je stupila 1997-02-19, s rokom provedbe za države članice do 1999-02-19. Od 2000-07-01 Direktiva je uključena u Sporazum o europskoj ekonomskoj zoni čime je prošireno unutarnje tržište električne energije i na Norvešku, Island i Lihtenštajn.

Cilj je Direktive bio uspostaviti pravila za proizvodnju, prijenos i distribuciju električne energije, odnosno pravila za ustrojavanje i djelovanje sektora električne energije, pristup tržištu, vođenje i upravljanje sustavima i davanje odobrenja za izgradnju novih kapaciteta.
Direktiva se temelji na tri osnovna načela:

– uvođenje konkurencije uz istodobno poštivanje načela javne usluge prema kojem je osiguranje odgovarajuće i pouzdane opskrbe električnom energijom od najveće važnosti za ukupne gospodarske tokove,
– postupno uvođenje konkurencije kako bi se osiguralo potrebno vrijeme za prilagodbu,

  · the unbundling of administration in such a manner that the network administration is separated from the administration of the rest of the enterprise,
  · legal unbundling in a manner that a separate legal entity is established whose operations will be limited to the networks,
  · the unbundling of ownership in such a manner that a vertically connected enterprise is required to sell the network,
— the creation of an independent regulatory body, because the organization of an efficient electricity market requires the efficient regulation of the transmission and distribution networks for three reasons:
  · the prevention of excessively high prices,
  · the prevention of subsidizing,
  · the prevention of discrimination,
— providing a high level of public services with the goal of protecting the public interest in connection with the security of supply, environmental protection and consumer protection,
— reciprocity of access to the markets of other countries, i.e. achieving a uniform tempo of liberalization, and
— the creation of effective regulations at the level of the European Union.

The creation of an internal electricity market in the European Union began with the Directive on the Transit of Electricity through Transmission Grids dated 1990, which had the main goal of assuring that the network operator in one member state cannot interfere with the exchange of electricity between other member states.

Today's internal electricity market of the European Union was established on the basis of Directive 96/92/EC [9] dated December 19, 1996. It went into force on February 19, 1997, and the deadline for its implementation by the member states was February 19, 1999. Since July 1, 2000, the Directive has been included in the European Economic Area Agreement, according to which the internal market was expanded to include Norway, Iceland and Lichtenstein.

The goal of the directive was to establish regulations for the production, transmission and distribution of electricity, i.e. regulations for the organization and operation of the electrical power sector, market access, the control and management of systems, and issuing authorization for the construction of new generating capacity.
The directive is based upon three basic principles:

– the introduction of competition while at the same time respecting the principles of public service, according to which suitable and reliable electricity supply is secured, which is of the utmost importance for overall economic flow,
– the gradual introduction of competition in order

– sukladno načelu supsidijarnosti, Direktiva ne nameće gotova rješenja zamljama članicama, ona daje samo okvir za izgradnju unutarnjeg tržišta ostavljajući široki prostor za usvajanje rješenja koja najbolje odgovaraju njihovoj situaciji [10].

Međutim, liberalizacija tržišta električne energije ipak se nije odvijala očekivanim tempom. Zbog predloženog velikog broja izmjena i dopuna postojeće Direktive, 2003-06-26 donesena je nova Direktiva 2003/54/EC [11]. Ova Direktiva najznačajnije promjene donosi u sljedećim područjima:

— dinamici otvaranja tržišta,
— načinu davanja dozvole za izgradnju novih kapaciteta,
— pristupu mreži,
— obvezi razdvajanja operatora sustava i
— obvezi javne usluge.

Odredbe ove Direktive primenjuju se u nacionalnim pravima država članica od 2004-07-01.

S ciljem reguliranja prekogranične trgovine električnom energijom, 2003-06-26 donesena je i Uredba 1228/2003/EC o uvjetima pristupa mreži radi prekogranične trgovine električnom energijom [12], kojom se uspostavljaju pravila za prekograničnu trgovinu. Time se izravno podupire stvaranje unutarnjeg tržišta električne energije, uzimajući u obzir specifičnosti nacionalnih i regionalnih tržišta. Uredbom se, između ostalog uspostavljaju mehanizmi za kompenzaciju prekograničnih tokova električne energije (inter TSO kompenzacija), uspostavljaju načela za njihovu naplatu kao i za korištenje raspoloživih kapaciteta interkonekcija između nacionalnih prijenosnih sustava [13]. Uredba se primjenjuje od 2004-07-01. Razlika između Uredbe i Direktive je u tome što se Uredba izravno i doslovno obvezujuće primjenjuje u zemljama članicama, a Direktiva traži provedbu kroz zakone zemalja članica.

3.4.2 Prepreke na putu do unutarnjeg tržišta električne energije

Prema izvješću Eurostata [14] iz srpnja 2006. godine, unutar Europske unije najskuplja struja za kućanstva je u Slovačkoj, dok najmanje za struju odvajaju građani Grčke. Najvišu cijenu struje, ustvari, plaćaju građani Danske koji odvajaju 23,62 eura za 100 kilowatsati (kWh), no ako se cijena struje prilagodi za kupovnu moć, onda najviše struju plaćaju stanovnici Slovačke, koji odvajaju čak 24,48 eura za 100 kWh. Nakon Slovačke slijede Italija sa 20,23 eura, Poljska sa 20,05 eura i Nizozemska 19,15 eura za 100 kWh. U susjednoj Sloveniji građani odvajaju

to provide the necessary period of adjustment,
– pursuant to the principle of subsidiarity, the directive does not impose finished solutions upon the member states; it only provides a framework for the construction of internal markets, leaving ample room for the adoption of solutions that are best suited to their circumstances [10].

However, the liberalization of the electricity markets did not occur at the anticipated tempo. Due to the large number of proposed amendments to the existing directive, on June 26, 2003 the new Directive 2003/54/EC was adopted [11]. This directive brought the most significant changes in the following areas:

— the dynamics of market opening,
— the manner of issuing permits for the construction of new generating capacity,
— network access,
— the obligation of unbundling system operators and
— the obligation of public service.

The stipulations of this directive have been applied in the national legislation of the member states since July 1, 2004.

With the goal of regulating cross-border exchanges of electricity, on June 26, 2003 Regulation 1228/2003/EC was adopted on conditions for access to the network for cross-border exchanges in electricity [12]. Thus, direct support was provided for the creation of an internal electricity market, taking into account the specificities of the national and regional markets. The regulations, among other things, also establish the mechanisms for the compensation of the inter-transmission system operator (inter-TSO compensation), the principles for its collection as well as for the use of the available interconnection capacities among national transmission systems [13]. The regulations have been in effect since July 1, 2004. The difference between the regulations and the directive is that the regulations directly and literally stipulate mandatory application in the member states and the directive stipulates implementation through the legislation of the member states.

3.4.2 Obstacles on the path to an internal electricity market

According to a report by Eurostat [14] dated July 2006, within the European Union the most expensive electricity for households is in Slovakia, while citizens of Greece set aside the least for electricity. The highest price for electricity is actually paid by the citizens of Denmark, 23,62 euros per 100 kilowatt hours (kWh). However, if the price of electricity is adjusted to purchasing power, then the inhabitants of Slovakia pay the most for electricity, 24,48 euros per 100 kWh. Slovakia is followed by Italy with 20,23 euros, Poland with 20,05 euros and the Netherlands with 19,15 eu-

13,71 eura, dok Mađari svojim distributerima električne energije plaćaju u prosjeku 17,14 eura za 100 kWh. Najmanje struju plaćaju Grci koje 100 kWh stoji 8,01 eura, a uz njih manje od 10 eura plaćaju još i Britanci 9,05 eura i Finci 9,38 eura za 100 kWh.

Industrijski potrošači apsolutno plaćaju najviše u Italiji, 12,08 eura za 100 kWh, a najmanje u Latviji, 4,09 eura za 100 kWh. No, ako se cijene prilagode kupovnoj moći, najskuplja je struja tvrtkama u Mađarskoj, gdje one plaćaju 12,13 eura za 100 kWh, a najjeftinija u Finskoj i Švedskoj gdje se plaća 4,90 odnosno 4,98 eura za istu količinu struje. Među zemljama sa skupljom strujom još se nalaze Cipar 11,92 eura, Češka 11,73 eura, Italija 11,59 eura i Poljska 10,67 eura, dok jeftiniju struju imaju Francuska 5,24 eura i Danska 5,82 eura za 100 kWh.

Istraživanje Eurostata za kućanstva bazira se na potrošnji 3 500 kWh godišnje i uključuje sve poreze i porezna davanja, dok se za industrijske korisnike bazira na potrošnji 2 000 MWh godišnje i isključuje porez na dodanu vrijednost.

Ovi podaci pokazuju da su razlike u cijenama električne energije među državama Europske unije i do 260 %, što znači da i dalje egzistira velika razlika u cijenama i to kako za kućanstva tako i za industriju. Zato zemlja koja ima znatno nižu cijenu ne želi stranog partnera sa znatno višom cijenom. Zbog toga se neke države ne žele odreći kontrole nad cijenama električne energije.

Usporedbe radi, kućanstva u Hrvatskoj plaćaju oko 30 % nižu cijenu, a industrijski potrošači do 20 % manje u odnosu na prosjek cijena električne energije u Europskoj uniji [15].

Europska komisija najavila je razbijanje velikih europskih energetskih skupina kako bi se poduprlo prekogranično tržišno natjecanje manjih energetskih tvrtki na tržištu Europske unije. Komisija smatra da bi za bolje razvijanje europskog elektroenergetskog tržišta trebalo provesti vlasničko razdvajanje proizvodnje električne energije i distribucijskog sustava. Primjerice, očekuje se da bi nova europska direktiva mogla zabraniti spajanja i preuzimanja kao što bi bilo ono E.ON-a i Endese. Naime, europska povjerenica za zaštitu tržišnog natjecanja Nellie Kroes smatra da nije moguće da u vlasništvu iste tvrtke budu i distribucija i opskrba i proizvodnja električne energije, odnosno istodobno vlasništvo nad proizvodnjom i prijenosom energije u suprotnosti je pravilima tržišnog natjecanja. Nova energetska politika, odnosno izrada novih direktiva najavljena je za početak 2007. godine [16]. Zbog velikih

ros per 100 kWh. In neighboring Slovenia, the citizens spend 13,71 euros while Hungarians pay an average of 17,14 euros per 100 kWh to their electricity distributors. Greeks pay the least for electricity, 8,01 euros per 100 kWh, and the British and Fins also pay less than 10 euros per 100 kWh, 9,05 and 9,38 euros respectively.

In absolute terms, industrial consumers pay the most in Italy, 12,08 euros per 100 kWh, and the least in Latvia, 4,09 euros per 100 kWh. However, when electricity prices are adjusted to purchasing power, the most expensive electricity is sold to companies in Hungary, where they pay 12,13 euros per 100 kWh and the least expensive in Finland and Sweden, where the same amount of electricity costs 4,90 and 4,98 euros respectively. Among the countries with expensive electricity are also Cypress (11,92 euros), the Czech Republic (11,73 euros), Italy (11,59 euros) and Poland (10,67 euros), while France and Denmark have cheap electricity, 5,24 and 5,82 euros per 100 kWh respectively.

The report by Eurostat for households is based upon consumption of 3 500 kWh annually, including all the taxes and contributions, while for industrial users consumption is based upon 2 000 MWh annually and excludes value added tax.

These data indicate that differences in electricity prices among countries of the European Union are as great as 260 %, which means that there are still major differences in prices, both for households and industry. Thus, a country that has a significantly lower price does not want a foreign partner with a significantly higher price. For this reason, some countries do not want to relinquish control over electricity prices.

For purposes of comparison, households in Croatia pay a price that is approximately 30 % lower and industrial consumers up to 20 % lower than the average price of electricity in the European Union [15].

The European Commission has announced the breaking up of the great European energy groups in order to support cross-border competition by small energy companies on the market of the European Union. The commission is of the opinion that it would be better for the development of the electricity market to implement the unbundling of the ownership of the electricity production system and the distribution system. For example, it is anticipated that the new European directives could prohibit mergers and takeovers, such as occurred with E.ON and Endesa. The European commissioner for competition, Nellie Kroes, is of the opinion that it is not possible for the distribution, supply and production of electricity to be under the ownership of the same company, i.e. the simultaneous ownership of the production and transmission of energy is contrary to the rules of market competition. New energy policy, i.e. the writing of new protivljenja lobija iza kojih stoje energetski divovi još uvijek nije donesena.

Da otvaranje energetskog tržišta ne ispunjava očekivanja pokazuju i sljedeće reakcije Europske komisije u 2006. godini. Prvo je u travnju uslijedilo upozorenje, a nakon toga u prosincu zahtjev za obrazloženim mišljenjem upućen na 16 zemalja članica Europske unije o otvaranju tržišta u plinskom i elektroenergetskom sektoru. Među tim zemljama su i sve najveće članice (Njemačka, Francuska, Italija, V. Britanija, Španjolska i Poljska) [17].

Da Europska komisija vodi oštru borbu protiv monopolističkog ponašanja najvećih energetskih tvrtki potvrđuju i sve češće inspekcijske kontrole tih kompanija. Tako je već drugi put u 2006. godini izvršen pretres prostorija četiriju najvećih njemačkih elektroenergetskih kompanija. U svibnju zbog sumnje u namještanje cijena, a u prosincu radi sumnje da nisu u potpunosti koristile svoje kapacitete, što je dovelo do veće cijene električne energije [17].

Unatoč protivljenju Europske komisije daljnjim spajanjima najvećih europskih energetskih tvrtki, čelnici tih tvrtki očekuju nastavak toga procesa. Evo kako to obrazlaže predsjednik uprave njemačke energetske kompanije E.ON Wulf Bernotat: Logična je težnja kompanija u energetskom sektoru da budu što veće i da razviju međunarodnu strukturu, zbog zaoštravanja međunarodne konkurencije na području nabave. Veliki klijenti lakše pregovaraju s proizvođačima poput Gazproma ili Statoila nego oni mali. Međunarodne kompanije osiguravaju odlučujuće poticaje i za razvoj europskog tržišta energije, jer je poticanje prekogranične trgovine u njihovom interesu [18].

Međutim, taj isti čelnik E.ON-a deset mjeseci kasnije, traži da se njemačke kompanije zakonom zaštiti od neprijateljskog preuzimanja izvana. Nedopustivo je da kompanije koje na vlastitim tržištima uživaju zaštitu države kupuju poduzeća na slobodnim tržištima poput njemačkog, izjavio je Bernotat u razgovoru za Financial Times Deutschland. Stoga je sasvim logično što njemačka vlada razmišlja o promjenama zakona o gospodarskim odnosima s inozemstvom, kako bi se uzeli u obzir takvi slučajevi, dodaje on. Berlin je odlučio ispitati mogućnost uvođenja posebnog kontrolnog postupka kako bi se pri problematičnim inozemnim ulaganjima vodilo računa o nacionalnim sigurnosnim interesima. Nemamo nikakvih konkretnih bojazni da bi nas netko mogao preuzeti, napominje ipak Bernotat, dodajući da je visoka tržišna kapitalizacija kompanije zasigurno najbolja zaštita. Naime,

directives, has been announced for the beginning of the year 2007 [16]. Due to the great objections of the lobbies backed by the energy giants, these directives have still not been adopted.

That the opening of the energy market has not fulfilled expectations was also indicated by the following reactions of the European Commission in the year 2006. A warning was issued in April followed by a request in December sent to sixteen member states of the European Union for an explanation of positions on the opening of markets in the gas and electrical power sectors. These countries included all the largest members (Germany, France, Italy, Great Britain, Spain and Poland) [17].

That the European Commission is conducting an intense battle against the monopolistic behavior of the largest energy companies is confirmed by the ever increasing inspection controls of these companies. Thus, for the second time in the year 2006, the premises of the four largest German electrical power companies were searched. In May, this was due to suspicions of price fixing and in December, due to suspicions that they had not used their capacities to the fullest, which led to higher electricity prices [17].

Despite opposition by the European Commission to the further merger of the largest European energy companies, the leadership of these firms anticipates the continuation of this process. As explained by the chief executive officer of the German power company E.ON, Wulf Bernotat: The logical aspiration of companies in the energy sector is to be as large as possible and to develop an international structure, due to the intensification of international competition in the area of procurement. Large clients can negotiate more easily with producers such as Gazprom or iStatoil than small ones. International companies also provide decisive incentives for the development of the European energy market because stimulating cross-border exchange is in their interest [18].

However, ten months later that same E.ON official wanted German companies to be protected from unfriendly outside takeovers by law. It is unacceptable for companies that enjoy the protection of the state on their own markets to purchase enterprises on free markets such as the German market, said Bernotat in an interview for the Financial Times Deutschland. Therefore, it is completely logical that the German government is considering changing the legislation on economic relations with foreign countries, in order to take such cases into consideration, he added. Berlin decided to investigate the possibility of introducing special control of the procedures so that national security interests would be taken into account regarding problematic foreign investments. We have no concrete fears that someone would be able to take us over, noted Bernotat, adding that high market capitalization of a company is certainly the best protrenutačna je tržišna vrijednost E.ON-a 86 milijardi eura, dodaje on [19]. Ali, za svaki slučaj neka bude i zaštita države. Ipak, što je sigurno, sigurno je. Iznenađujuća je ovdje i kvalifikacija preuzimanja, koje se naziva neprijateljskim. Čini se da prijateljskog preuzimanja nema i da ga ne može biti, jer su interesi partnera, barem kada se radi o međunarodnom preuzimanju, suprotni.

U takvoj situaciji velikih problema u stvarnoj liberalizaciji tržišta električne energije Europska komisija 2007-01-10. godine iznosi nove strateške odrednice za objedinjavanje energetskog tržišta u Europskoj uniji, prvenstveno u cilju:

— sniženja cijena električne energije i plina,
— poboljšanja sigurnosti opskrbe (20 %, odnosno veći dio iz obnovljivih izvora do 2020. godine) i
— smanjenja emisije ugljičnog dioksida (smanjenje emisiju za 30 % do 2020. u odnosu na 1990. godinu).

Odluka o potrebi snižavanja cijena zahtjev je prema velikim elektroenergetskim tvrtkama da politiku cijena prepuste ponudi na tržištu, a da bi se to postiglo, zahtijeva se izdvajanje prijenosa i distribucije u potpuno samostalne tvrtke (tvrtke kćeri više se ne prihvaćaju). Pokretač ovog zahtjeva je Glavna uprava za tržišno natjecanje Europske unije, koja je zbog pritužbi potrošača i uočenih nepovoljnih kretanja, u svibnju 2006. godine provela niz iznenadnih inspekcija u nekim od najvećih tvrtki, kao što su njemački E.ON i RWE te francuski GdF, gdje je utvrđeno ponašanje suprotno zahtjevima slobodnog tržišta.

Potpunom otvaranju svojeg elektroenergetskog tržišta najviše se opiru u praksi Francuska i Španjolska. Francuska se teško odriče vertikalne organizacije svojih elektroenergetskih tvrtki i nadzora nad cijenama. Privatizacija je krenula, ali država i dalje ostaje vlasnik 70 % do 90 % u tom sektoru. Na primjeru Francuske može se uočiti što se sve skriva iza politike reguliranih i slobodnih cijena. Veleprodajna cijena je 2001. godine iznosila 25 EUR/MWh, da bi danas porasla čak na 50 EUR/MWh. Francuska ima znatno povoljniju cijenu električne energije iz nuklearnih elektrana i hidroelektrana od ostalih članica Europske unije. Zbog toga ima niz velikih potrošača, koji ne žele da im slobodno tržište preotme tu jeftiniju energiju, jer bi se tada tvornice morale zatvoriti ili preseliti u druge zemlje. Toga se boji i francuska vlada.

Takav svoj stav Francuzi obrazlažu na sljedeći način. Ako se konkurencijom izjednači, odnosno približi razina cijena, tada će potrošači koji su

tection. The current market value of E.ON is 86 billion euros, he said [19]. However, in any case let there be state protection. Nevertheless, sure is sure. Here the qualification of takeovers is surprising, which are called hostile. It seems that there is no such thing as a friendly takeover and it cannot exist because the interests of the parties, at least concerning international takeover, are opposed to each other.

In such a situation with great problems in the actual liberalization of the electricity market, on January 10, 2007, the European Commission issued new strategic guidelines for the integration of the energy market in the European Union, primarily with the following goals:

— lowering the prices of electricity and gas,
— improving the security of supply (20 %, i.e. the majority from renewable energy sources by the year 2020) and
— reducing emissions of carbon dioxide (a 30 % reduction in emissions by the year 2020, in comparison to the year 1990).

The ruling on the need to reduce prices is an order for large electrical power companies to allow the price policy to be left to market supply. To achieve this, it is necessary to unbundle transmission and distribution into completely independent companies (daughter companies are no longer acceptable). The initiator of this demand is the Directorate General for Competition of the European Union, which due to consumer complaints and evident undesirable trends conducted a series of surprise inspections in May 2006 at some of the largest companies, such as the German E.ON and RWE and the French GdF, where behavior was found to be contrary to the requirements of a free market.

In practice, France and Spain are the most highly opposed to the complete opening of their electricity markets. France finds it difficult to relinquish the vertical organization of its electrical power companies and supervision over prices. Privatization has started but the state is still the owner of 70 % to 90 % of this sector. Using the example of France, it is possible to see what is hiding behind the politics of regulated and free prices. The wholesale price was 25 EUR/MWh in 2001, which has increased today to 50 EUR/MWh. France has a significantly more desirable price for electricity from nuclear and hydroelectric power plants than other members of the European Union. For this reason, it has a series of large customers who do not want the free market to snatch away this cheap energy, because in such a case the factories would have to close or move to other countries. The French government is also afraid of this.

The French explain their position in the following manner. If through competition the price of electricity becomes approximately the same, then customers who had been obtaining electricity from power plants that uz elektrane s nižom cijenom koštanja, a koje su do sada izgrađene njihovim doprinosom, plaćati višu cijenu, dok će oni drugi potrošači koji su izgradili elektrane sa skupljom cijenom, plaćati povoljniju cijenu. Bune se i dioničari u državama članicama s jeftinijim izvorima električne energije, koji su ulagali u energetiku ili u razvoj određenih grana, jer opravdano strahuju da će njihovo gospodarstvo izgubiti dosadašnju konkurentnost. Pobornici potpune liberalizacije i objedinjavanja tržišta električne energije Europske unije ističu pak da viša cijena zapravo potiče štednju, a usmjerava i cijelo gospodarstvo u pravcu energetski štedljivih proizvoda i traženje boljih rješenja. Viša cijena isto tako potiče ulaganje u nove kapacitete i razvoj, a bolje puni državni proračun.

Španjolska je donijela odluku o razdoblju od 14 godina povoljnih cijena električne energije za vlastite potrošače. Glavna uprava za tržišno natjecanje Europske unije otvorila je istragu o ispravnosti te odluke, jer smatra da će biti narušeno slobodno tržišno natjecanje. Španjolski potrošači bit će povlašteni, a ujedno će zbog niske cijene biti obeshrabreni potencijalni novi proizvođači energije. Španjolska vlada blokirala je u prvoj polovici 2007. godine 37 milijardi eura vrijednu ponudu njemačkog E.ON-a za preuzimanje njene najveće energetske tvrtke Endese, preferirajući konkurentsku ponudu koju je podastro španjolski Gas Natural SA, uz argument da je ostanak Endese u španjolskim rukama nacionalni interes, ne obazirući se ni na službena upozorenja i zahtjeve Europske komisije da se radi o kršenju europskih propisa i da će biti prijavljena Europskom sudu [20].

U Njemačkoj se Savezna vlada u siječnju odmah vrlo nepovoljno očitovala o razdvajanju vertikalne organizacije svoje elektroenergetike. Njemački su ministri (kao i oni francuski) naglasili da neovisna agencija u Njemačkoj nadzire maržu na prijenosnoj mreži i da je to dovoljno osiguranje slobodnoj konkurenciji. Ujedno su izjavili da bi to razdvajanje imalo vrlo nepovoljan učinak na njemačko gospodarstvo i da za sada to nije prihvatljivo.

Nakon takve reakcije najvećih članica Europske unije, Europsko vijeće je preoblikovalo zahtjev za razdvajanjem vertikalne organizacije u elektroenergetskom sektoru u preporuku, pravdajući se da nije moguće zauzeti čvrst stav kada se suoči 27 ministara koji imaju vrlo oprečna gledišta. Međutim, na sastancima i u razgovorima svi pozdravljaju razdvajanje i poticaj za ulaganje u prijenosnu mrežu i traže čvrste odrednice i objedinjeno tržište.
Istodobno, Europsko vijeće je smanjilo zahtjev za udjelom obnovljivih izvora s 20 % na 10 %,

cost less and that up to now have been constructed through their contributions will pay a higher price, while those other customers who built more expensive power plants will pay a lower price. Shareholders and member states with cheap sources of electrical energy, who have invested in energetics or the development of particular branches, are rebelling because they are justifiably afraid that their economies will lose the competitiveness that they have enjoyed until now. Proponents of the complete liberalization and uniformity of the electricity market of the European Union emphasize that a higher price actually provides an incentive for saving, and orients the entire economy in the direction of energy saving products and the search for better solutions. A higher price also provides an incentive for investment in new generating capacity and development, as well as filling state budgets better.

Spain has adopted a decision on a period of 14 years of favorable electricity prices for its own customers. The Directorate General for Competition of the European Union has inaugurated an investigation regarding the propriety of this decision because it is of the opinion that free market competition will be disrupted. Spanish customers will be privileged and at the same time potential new energy producers will be discouraged due to low prices. In the first half of 2007, the Spanish government blocked an offer worth 37 billion euros from the German E.ON for the takeover of its largest power company, Endesa, preferring a competitive offer submitted by the Spanish company Gas Natural SA, with the argument that it was in national interests for Endesa to remain in Spanish hands, disregarding the official warning and demands of the European Commission that this involved a violation of European regulations and that it will be reported to the European Court [20].

In January, the Federal Government of Germany expressed a very unfavorable opinion regarding the unbundling of the vertical organization of its electrical power sector. German ministers (like the French ministers) emphasized that an independent agency in Germany supervises the margin on the transmission network and that this is sufficient guarantee for free competition. They also announced that this unbundling would have a highly undesirable effect on the German economy and would be unacceptable for the present.

After such reactions by the largest member states of the European Union, the0 European Council reformulated the demand for the unbundling of vertical organizations in the electrical power sector in their recommendation, with the explanation that it is not possible to take a firm position when confronting twenty-seven ministers who have a markedly opposite viewpoint. However, at meetings and in discussions, all salute unbundling and investment incentives in the transmission network and seek firm determinates and a single market.

osobito biogoriva, koje svakog dana ima sve više protivnika, koji upozoravaju na neisplativost i pogrešnu usmjerenost zaštite prirode. Potrebne su velike površine plodne zemlje, troši se dragocjena voda, prijeti opasnost od krčenja šuma, a iskoristivost bilja je mala.

Sredinom 2007. godine ministri gospodarstava šest zemalja Europske unije, predvođeni Njemačkom i Francuskom, uputili su pismo Europskoj komisiji u kojem su izrazili svoje protivljenje njenim planovima reforme energetskog sektora u kojem navode: Ideju da se samo potpunim odvajanjem proizvodnje od distribucije može utrti put razvoju tržišta električne energije i plina u Europskoj uniji treba odbaciti. Njemačka i Francuska izrazile su zabrinutost da bi tim potezom najveće energetske grupe u te dvije zemlje, EdF i E.ON, bile značajno oslabljene [17].

Međutim, ima i pozitivnih koraka prema jedinstvenom europskom energetskom tržištu. Tako su u lipnju 2007. godine Memorandum o razumijevanju potpisali predstavnici Njemačke, Francuske, Belgije, Nizozemske i Luksenburga, kojim su definirali stvaranje jedinstvenog tržišta električne energije od 2009-01-01. Od tog jedinsvenog tržišta očekuju se niže cijene za potrošače, veća sigurnost opskrbe i veća ulaganja u proizvodne kapacitete i prijenosnu infrastrukturu [16].

3.4.3 Zaključno o razvoju tržišta električne energije u Europskoj uniji

Nakon iznesenih i analiziranih tendencija u procesu reforme elektroenergetskog sektora u Europskoj uniji može se zaključiti da se radi o dugotrajnom procesu, koji u većini zemalja još nije u potpunosti dovršen, ali su očita nastojanja prema potpunom otvaranju tržišta električne energije u gotovo svim zemljama. Pri tome neke zemlje sporije prolaze kroz tranzicijski period (Francuska, Španjolska, Grčka, Estonija, Latvija), dok su neke završile s osnovnim reformama (Engleska, Norveška, Švedska). Međutim, pristupi i praksa u liberalizaciji tržišta električne energije pokazuju i dalje veliku raznolikost. Ta raznolikost manjim dijelom je posljedica organizacijskog, vlasničkog, tehnološkog, povijesnog, zemljopisnog, zakonodavnog i općedruštvenog naslijeđa, a najvećim dijelom činjenica da svaka zemlja u tim procesima restrukturiranja i otvaranja tržišta nastoji maksimalno zaštititi svoj gospodarski interes.

Uglavnom iz tog razloga efekti poduzetih reformi u elektroenergetskom sektoru ipak nisu zadovoljavajući, što potvrđuju sljedeće činjenice:

At the same time, the Council of Europe has reduced its demand for the percentage of renewable energy sources from 20 % to 10 %, particularly biofuels, which every day have an increasing number of opponents who warn of the unprofitability and faulty orientation of this type of environmental protection. Biofuels require large areas of fertile land, consume precious water, pose the danger of clearing forests, and the efficiency of utilizing plants is very low.

In mid 2007, the ministers of the economy of six countries of the European Union, led by Germany and France, sent a letter to the European Commission in which the expressed their opposition to its plans for reforming the energy sector, stating that the idea that only complete separation of production from distribution can pave the way for the development of the electricity and gas markets in the European Union must be rejected. Germany and France expressed concern that this would significantly weaken the largest energy groups in their two countries, EdF and E.ON [17].

However, there have been positive steps toward an integrated European energy market. Thus, in June 2007, the Memorandum of Understanding was signed by representatives of Germany, France, Belgium, the Netherlands and Luxembourg, which defined the creation of an integrated electricity market after January 1, 2009. From this integrated market, lower prices for customers, greater security of supply and greater investments in generating capacity and the transmission infrastructure are anticipated [16].

3.4.3 Conclusions on the development of the electricity market in the European Union

After considering and analyzing the tendencies in the process of reform of the electrical power sector in the European Union, it can be concluded that they are long-term processes, which in the majority of countries have not been completed in their entirety. However, there are evident attempts toward fully achieving the opening of the electricity markets in nearly all of the countries. Moreover, some countries are passing more slowly through the transition process (France, Spain, Greece, Estonia and Latvia), while others have already completed basic reforms (England, Norway and Sweden). However, the approaches and practices in the liberalization of energy markets have continued to exhibit marked differences. These differences to a lesser extent are the consequence of the organizational, ownership, technological, historical, geographical, legislative and general social legacies, and for the most part due to the fact that every country in these processes of the restructuring and opening of markets attempts to protect its economic interests to the greatest possible extent.

For this reason, the effects of the reforms undertaken in the electrical power sector have not been generally satisfactory, as confirmed by the following:

—Customers have not received the promised lower

— potrošači nisu dobili obećane niže cijene. Objektivni razlozi su rast cijena nafte i plina, a ostali leže u činjenici prerastanja državnih monopola u još veće međudržavne monopole,
— ne ostvaruje se prvobitna namjera direktiva Europske unije – stvaranje unutarnjeg tržišta električne energije, jer svaka zemlja nastoji organizirati nacionalno tržište,
— stvaraju se novi monopoli, velike elektroenergetske tvrtke, koji šire granice u smjeru najveće zarade, a zatvaraju ih tamo gdje gube. U Europskoj uniji sedam najvećih kompanija (E.ON, RWE, EDF, Vattenfall, Enel, Suez/Electrabel i Endesa) ima većinski udio na tržištu,
— i dalje egzistira velika razlika u cijenama elekrične energije među državama Europske unije i to kako za kućanstva tako i za industriju.

Temeljem iznesenog može se zaključiti da Direktive Europske unije ne treba shvatiti kao jedinu vodilju reorganizacije vlastitog elektroenergetskog sektora, već kao minimum zahtjeva Europske unije, rukovodeći se prvenstveno vlastitim strategijama razvoja i interesima. Hrvatska kao mala zemlja ima još više razloga da se ponaša tako u prilagodbi njenog elektroenergetskog sustava uvjetima globalizacije.

Na kraju, nameće se pitanje, kako je moguće da politika okreće kormilo prema demonopolizaciji, a brod ipak plovi gotovo u suprotnom smjeru? Kao najlogičniji odgovor nameće se da se radi o dvostrukoj igri. To potvrđuje i neširenje velikih igrača na tržišta najvećih konkurenata, iako se radi o susjednim zemljama (Njemačka, Francuska i Španjolska).

3.5 Tranzicijske zemlje

Proces prilagodbe novim uvjetima za tranzicijske zemlje je daleko teži, jer su njihovi elektroenergetski sustavi u te promjene ušli sa značajnim negativnim naslijeđem:

— prosječna razina cijena električne energije bila je, a u nekim zemljama je još uvijek, niža od realne, tako da se razvoj sustava osiguravao različitim vrstama državnog intervencionizma (proračunsko subvencioniranje, kapitalna gradnja iz državnih fondova, državna jamstva za kredite i dr.). Posljednjih godina prije početka reforme elektroenergetskog sektora značajnijeg razvoja nije ni bilo,
— električna energija tretirana je kao opće dobro koje treba biti dostupno potrošačima u dovoljnim količinama bez obzira na njenu cijenu. Takvo stajalište diktiralo je politiku

prices. The objective reasons are the increase in the prices of oil and gas, and the others are due to the growth of state monopolies into even larger interstate monopolies.
— The primary intention of the directive of the European Union is not being realized – the creation of an internal electricity market, because every country is attempting to organize a national market.
— New monopolies are being created, large electrical power companies that extend their borders in the direction of the greatest earnings and close them where there are losses. In the European Union, the seven largest companies (E.ON, RWE, EDF, Vattenfall, Enel, Suez/Electrabel and Endesa) have the majority market share.
— There still exist great differences in the prices of electricity among the countries of the European Union, for both households and industry.

On the basis of that which has been presented, it can be concluded that the directive of the European Union does not have to be understood as the sole guiding principle in the reorganization of the Croatian electrical power sector but as the minimum requirement of the EU, primarily guided by our own development strategies and interests. Croatia, as a small country, has even more reasons to behave in this manner in the adaptation of its electrical power system to the requirements of globalization.

Finally, the question is posed how is it possible for the rudder to be turned toward demonopolization while the ship is nonetheless sailing in the opposite direction. As the most logical response, it is evident that there is a double game. This is confirmed by the fact that the biggest players are not expanding to the markets of their biggest competitors, although they are neighboring countries (Germany, France and Spain).

3.5 Countries in transition

The process of adapting to the new conditions for countries in transition is far more difficult because their electrical power systems and these changes have a significantly negative legacy:

— the average level of electricity prices was, and in some countries still is, lower than the real prices, so that the development of the systems was secured through various types of state interventions (budgetary subsidies, investment construction from state funds, state guarantees for loans etc.). in the final years prior to the beginning of the reform of the electrical power sector, there had been no significant development,
— electricity is treated as a general good that should be accessible to customers in sufficient quantities without regard to its price. such a position dictated a policy of unrealistic and low prices

nerealnih i niskih cijena električne energije prema kategoriji potrošnje kućanstva, što je poticalo brojne oblike neracionalne potrošnje i energetski neracionalnog ponašanja (intezivno korištenje električne energije za grijanje i zagrijavanje vode),
- takvi nerealni odnosi u energetskom sektoru otežavaju donošenje strateških investicijskih odluka za ulaganje u elektroenergetske objekte,
- prevelik broj zaposlenih i niska radna efikasnost,
- pomanjkanjeorganizacijskihimenedžerskih sposobnosti kod rukovodećeg kadra,
- nepostojanje navedenih polazišta koje imaju razvijene zemlje Europske unije, odnosno tehnološko, organizacijsko i drugo zaostajanje u odnosu na te zemlje.

Svi ovi čimbenici rezultiraju činjenicom da se proces retrukturiranja elektroenergetskog sektora i otvaranja tržišta električne energije u tranzicijskim zemljama ostvaruje sporije i uz određene probleme. U tom procesu prednjače zemlje koje su postale članice Europske unije 2005-05-01. U nekima od tih zemalja reforma elektroenergetskog sektora tekla je drugačije od uobičajene, jer je nakon restrukturiranja elektroenergetskih tvrtki privatizacija stavljena u prvi plan, ispred izgradnje i otvaranja tržišta električne energije. Tako su tvrtke iz zemalja Europske unije, koje nisu privatizirane u svojim zemljama, imale značajni udio u privatizaciji elektroenergetskih tvrtki u tim zemljama, jer su cijene akvizicija bile vrlo povoljne.

Najvažnije prepreke bržem otvaranju tržišta električne energije u tranzicijskim zemljama su socijalni problemi koji se generiraju smanjenjem broja zaposlenih u elektroenergetskom sektoru i uvođenjem realne cijene električne energije za kućanstva. Realna cijena ima negativan utjecaj i na konkurentnost i profitabilnost gospodarstva tih zemalja. Ipak, indikativna je opća žurba provođenja reformi i to najčešće nastojanjem uvođenja najnaprednijih zapadnoeuropskih modela (bar na zakonodavnoj razini).

3.6 S A D

U restrukturiranje elektroenergetskog sektora u SAD-u krenulo se znatno kasnije, iz razloga što u SAD-u na razini države, pa čak ni na razini pojedinih saveznih država, nije bilo jedinstvenog elektroenergetskog sustava. Evo što je o američkom elektroenergetskom sustavu rekao predsjednik Bush u govoru 2001-05-17 kojim je najavio novu stratregiju energetike SAD-a: Danas je naš elektroenergetski sustav skoro jednako kvrgav kao što su naše ceste bile prije 80 godina. Rascijepali smo našu zemlju u desetke

of electricity for the category of household consumption, which stimulated numerous forms of irrational energy consumption (the intensive use of electricity for heating and hot water),
- such unrealistic relations in the energy sector make it difficult to arrive at strategic investment decisions for investment in electrical power facilities,
- there is a surplus of employees and their efficiency is low,
- the managerial personnel lack organizational and managerial abilities,
- these countries do not have the same starting point as the developed countries of the European Union, i.e. they are inferior from the technological, organizational and other aspects in relation to these countries.

All these factors result in the fact that the processes of the restructuring of the electrical power sector and the opening of the electricity markets in countries in transition are being achieved more slowly and with certain problems. In these processes, the leading countries are those which became members of the European Union on May 1, 2005. In some of these countries, the reform of the electrical power sector occurred differently, because privatization was afforded priority after the restructuring of the electrical power companies, before the construction and the opening of the electricity markets. Thus, the companies from the countries of the European Union that had not been privatized in their countries had a significant share in the privatization of the electrical power companies in these countries because the acquisition prices were very attractive.

The most significant obstacles to the rapid opening of electricity markets in countries in transition are the social problems that are generated by the cutbacks in the number of persons employed in the electrical power sector and the introduction of real electricity prices for households. Real prices have a negative impact on both the competitiveness and profitability of the economies of these countries. Nonetheless, the general haste to implement reforms, frequently with the attempt to introduce the most advanced Western European models (at least at the legislative level), is indicative.

3.6 The United States

The electrical power sector in the United States started restructuring significantly later, because at the national level and even at the state level the electrical power systems were not unified. This is what President Bush said in a speech delivered on May 17, 2001, in which he announced a new energy strategy for the USA: Today, our electrical system is almost as bumpy as our highways were 80 years ago. We have chopped our country into dozens of local electricity markets, which are haphazardly connected to one another [21]. The linking of the electrical power syslokalnih elektrotržišta, koja su nasumično međusobno povezana [21]. U povezivanje elektroenergetskih sustava SAD-a visokonaponskom mrežom krenulo se tek 2002. godine, dakle tek nakon Kalifornijske krize.

U deregulaciju industrije električne energije u SAD-u krenulo se s ciljem povećanja učinkovitosti i sniženja cijena električne energije. Deregulacija tržišta energije se u SAD-u naziva restrukturiranjem, zato što nastala konkurencijska tržišta imaju više saveznih pravila od reguliranih tržišta koja su zamijenila [22]. Restrukturiranje zakona je provedeno u polovici saveznih država, predvođenih Kalifornijom, Pensylvaniom, New Jersyjem i Marylandom.

Prva je krenula Kalifornija 1996. godine, prvenstveno s ciljem sniženja relativno visoke cijene električne energije. Krajem 1990-ih Kalifornija je pokušala osigurati kompatibilnost dvostranog trgovanja i središnjeg poola. Trebalo je riješiti i problem izgubljenih troškova prijašnjih reguliranih poduzeća u vlasništvu ulagača. Kako bi se nadoknadili ti troškovi, tarife električne energije su zaleđene na reguliranoj tarifi 10 % nižoj od razine iz 1996. godine i dodan im je trošak prijelazne konkurencije. Na kraju, kad su izgubljeni troškovi vraćeni i kad su nestale regulirane tarife, potrošači su se suočili s vrlo visokim cijenama veleprodajnog tržišta. Kako bi se odvratilo proizvođače od izvoza operator sustava skinuo je limit cijene od 250 USD/MWh, što je ubrzo dovelo do porasta cijena do astronomskih 1 400 USD/MWh (godinu prije toga cijena je iznosila samo 30 USD/MWh) [21]. Dakle, umjesto nižih cijena došlo je do suprotnog i poraznog rezultata, odnosno do 46 puta većih cijena za krajnje potrošače, raspada elektroenergetskog sustava i redukcija isporuka električne energije. Kalifornijci su prvi spoznali da povremeno ni rasvjete ne mogu imati ni po kojoj cijeni.

Tako se u praksi na drastičan način pokazalo koliko može biti štetna loše provedena deregulacija, odnosno koliko deregulacija može biti lošije rješenje od reguliranog sustava. Zakazalo je dugoročno sagledavanje potreba, odnosno strategija razvitka elektroenergetskog sektora, jer cijelo desetljeće u Kaliforniji nije sagrađena veća nova elektrana. Za vrijeme te krize 2000. godine ukinut je i maloprodajni izbor, iako su još 1998. godine svi kupci imali pravo birati svojeg opskrbljivača. Ta kalifornijska kriza, koja je eskalirala 2000. i 2001. godine, znatno je usporila procese reforme elektroenergetskog sektora u SAD-u.

tems of the United States by a high voltage network only began in the year 2002, i.e. after the California crisis.

The United States embarked upon the deregulation of the electrical power industry with the goal of increasing the efficiency and lowering the price of electricity. Deregulation of the energy markets in the United States is called restructuring because the new competitive markets have more federal regulations than the regulated markets that they have replaced [22]. Restructuring legislation was implemented in half of the states, led by California, Pennsylvania, New Jersey and Maryland.

In 1996, California was the first to start, primarily with the goal of lowering relatively high electricity prices. In the late 1990s, California attempted to assure the compatibility of bilateral trading and a central pool. It was also necessary to solve the problem of the recovery of stranded costs incurred by the previously regulated investor-owned companies. In order to compensate for these costs, the tariffs for electrical energy were frozen at a regulated amount that was 10 % lower than the 1996 level, to which was added the Competition Transition Charge. In the end, when the stranded costs were returned and tariffs were no longer regulated, consumers were confronted with very high prices on the wholesale market. In order to dissuade producers from imports, the system operator eliminated the price cap of 250 USD/MWh, which quickly led to price increases up to an astronomical 1 400 USD/MWh (during the previous year, the price was only 30 USD/MWh) [21]. Thus, instead of lower prices, the opposite resulted, i.e. prices that were up to 46 times higher for the final customer, break-up of the electrical power system and reduction in electricity delivery. Californians were the first to find out that occasionally they could not have light at any price.

Thus, it was drastically demonstrated in practice how detrimental poorly implemented deregulation can be, i.e. the extent to which deregulation can be a worse solution than a regulated system. The long-term forecast of requirements failed, i.e. the development strategy of the electrical power sector, because for an entire decade no major power plants were built in California. During the 2000 crises, it was no longer possible for customers to choose their retail suppliers, although in 1998 all customers still had this right. The California crisis, which escalated in 2000 and 2001, significantly slowed the process of the reform of the electrical power sector in the United States.

3.7 Hrvatska

3.7.1 Zakonodavni okvir

Hrvatska kao potpisnik Sporazuma o stabilizaciji i pridruživanju i kao kandidat za članstvo u Europskoj uniji ima obvezu postupne prilagodbe državnih monopola tržišne naravi uvjetima koji odgovaraju onima koji postoje na zajedničkom tržištu Europske unije.

Nakon dosta istraživanja, promišljanja i rasprava u stručnim krugovima, krajem lipnja 2000. godine donesen je Program reforme energetskog sektora, što je značilo početak energetske reforme u Hrvatskoj. Programom je utvrđeno razdvajanje temeljnih djelatnosti, odvajanje sporednih djelatnosti, formiranje tržišta energenata i privatizacija energetskih poduzeća.

U srpnju 2001. godine, donesen je paket od pet energetskih zakona u skladu s tada vrijedećim europskim direktivama o tržištu energenata. Tri od tih pet zakona definiraju predviđene promjene u elektroenergetskom sektoru. To su:

— Zakon o energiji,
— Zakon o tržištu električne energije i
— Zakon o regulaciji energetskih djelatnosti.

Provedba zakona podijeljena je u tri grupe aktivnosti:

— restrukturiranje energetskih tvrtki,
— donošenje podzakonskih i ostalih akata predviđenih zakonima i
— izgradnja potrebnih institucija za otvaranje tržišta.

Zaokruživanje prve faze definiranja normativnih pretpostavki reforme energetskog sektora završeno je u ožujku 2002. godine donošenjem Zakona o privatizaciji HEP-a i INE.

Reforma energetskog sektora odnosno provedba ovih zakona napredovala je sporo, jer je to za mnoge bilo nešto sasvim novo, put u nepoznato, a znanja o reformi i otvaranju energetskog tržišta su bila skromna. Reforma je postavila energetske subjekte, državnu administraciju i kupce električne energije u novu situaciju za koju nisu bili spremni. Zbog toga se reforma doživljavala kao teret i protivna interesima energetskih subjekata. Slične reakcije bile su prisutne i u zemljama Europske unije na početku provođenja reformi energetskog sektora. Provedbu zakona kočile su i koncepcijske razlike koje su se pojavile među energetskim subjektima vezano za otvaranje tržišta i pozicioniranje i ovlasti regulatornog tijela. Može se reći da je otvaranje tržišta električne energije usporeno zbog neslaganja oko koncepta restrukturiranja HEP-a, naročito organizacije djelatnosti operatora sustava.

3.7 Croatia

3.7.1 Legislative framework

Croatia, as a signer of the Stabilization and Association Agreement and as a candidate for membership in the European Union, is committed to the gradual adaptation of the state-owned monopolies of a market nature according to the conditions that correspond to those that exist on the integral market of the European Union.

After considerable research, deliberation and discussion in professional circles, in late June 2000 the Program for the Reform of the Electrical Power Sector was adopted, which signified the beginning of energy reform in Croatia. According to the Program, the unbundling of basic operations, the separation of auxiliary operations, the formation of a market for energy commodities and the privatization of energy companies were determined.

In July 2001, a package of five energy acts was adopted in compliance with the prevailing European directives on the energy commodities market. Three of these five acts define the anticipated changes in the electrical power sector, as follows:

— The Energy Act,
— The Electricity Market Act and
— The Regulation of Energy Operations Act.

The implementation of the acts is divided into three groups of activities:

— the restructuring of the energy companies,
— the adoption of supporting legislation and other anticipated legislation, and
— the building of the necessary institutions for opening markets.

The first phase was completed by the definition of the standard assumptions for the reform of the energy sector, which was completed in March 2002 with the adoption of the Privatization of HEP (the Croatian power company) and INA (the Croatian oil company) Act.

Reform of the energy sector, i.e. the implementation of the provisions of these laws, has progressed slowly because for many this was something entirely new, an unknown path, and knowledge about reform and the opening of the energy market was modest. Reform placed energy companies, state administrators and electricity customers in a new situation for which they were not prepared. Therefore, they experienced reform as a burden and contrary to the interests of the energy companies. Similar reactions also occurred in the countries of the European Union at the beginning of the implementation of reforms of the energy sector. The implementation of legislation was hindered by conceptual differences that occurred among the energy companies in connection with the opening of markets, positioning and the authority of the regulatory body. It can be said that the

Preciznije odredbe za rješavanje tog pitanja dala je nova direktiva Europske unije 2003/54/EC. Sve to utjecalo je na činjenicu da nužni podzakonski propisi nisu doneseni i tržište nije zaživjelo. Pokazalo se tako da se korjenite reforme ne provode jednostavno i bez otpora objektivne, ali i subjektivne naravi. Uz to, i Europska unija je u srpnju 2003. godine donijela novu energetsku Direktivu 2003/54/EC.

Naprijed navedeno utjecalo je na pokretanje rasprava i promišljanja o daljnjem tijeku reforme energetskog sektora i procesa revizije postojećih energetskih zakona, što je rezultiralo donošenjem novog Zakona o tržištu električne energije i novog Zakona o regulaciji energetskih djelatnosti te Zakona o izmjenama i dopunama Zakona o energiji u prosincu 2004. godine. Novim zakonima su zakonska rješenja iz 2001. godine usklađena s Direktivom 2003/54/ EC, uklonjeni su određeni nedostaci i nepreciznosti, te je osigurana njihova realnost i primjenjivost u kontekstu restrukturiranja HEP grupe i otvaranja tržišta električne energije u Hrvatskoj.

Definirana je nova dinamika otvaranja tržišta električne energije kroz stjecanje položaja povlaštenog kupca. S danom stupanja na snagu Zakona o tržištu električne energije svi kupci s godišnjom potrošnjom većom od 20 GWh i svi kupci koji su priključeni izravno na prijenosnu mrežu stekli su status povlaštenog kupca.

Dinamika daljnjeg otvaranja tržišta električne energije je sljedeća:

— 2006-07-01 otvoreno je tržište za kupce s potrošnjom većom od 9 GWh, što je značilo mogućnost biranja opskrbljivača električnom energijom za stotinjak poduzetnika, koji su u 2006. godini potrošili oko milijardu kWh električne energije,
— 2007-07-01 tržište je otvoreno za sve kupce kategorije poduzetnici, odnosno za preko 200 000 potrošača, čija je potrošnja u 2006. godini iznosila 8,5 milijardi kWh električne energije ili 57 % ukupne potrošnje,
— 2008-07-01 status povlaštenog kupca dobili su i potrošači kućanstva, što znači svi kupci električne energije u Hrvatskoj.

I u novim zakonima uočene su određene nejasnoće i nedostaci koji mogu stvarati poteškoće u provedbi zakona, što može rezultirati usporenim restrukturiranjem i libralizacijom tržišta električne energije.

Radi provođenja reforme sa što manje problema i realizacije zacrtane dinamike otvaranja tržišta električne energije bilo je nužno pravo-

opening of the electricity market was slowed due to disagreements regarding the concept of restructuring HEP, especially the organization of the activities of the system operator.

More precise provisions for resolving this question were provided by the new Directive of the European Union 2003/54/EC. This all affected the fact that necessary secondary legislative provisions were not adopted and the market did not start operating. It was shown that radical reforms are not implemented simply and without resistance of both a subjective and objective nature. Moreover, in July 2003, the European Union adopted the new energy Directive 2003/54/EC.

The aforementioned also affected the initiation of discussions and deliberations on the further course of the reforms of the energy sector and the process of the revision of the existing energy legislation, which resulted in the adoption of a new Electricity Market Act, a new Regulation of Energy Operations Act and Amendments to the Energy Act of December 2004. With the new legislation, the legal solutions from 2001 were coordinated with Directive 2003/54/EC, certain shortcomings and imprecision were eliminated, and applicability was insured within the context of the restructuring of the HEP Group and the opening of the electricity market in Croatia.

New dynamics were defined for the opening of the electricity market by defining the status of a preferred customer. From the day that the Electricity Market Act went into effect, all customers with an annual consumption exceeding 20 GWh and all customers connected directly to the transmission network obtained the status of preferred customers.

The dynamics of the continued opening of the electricity market are as follows:

— on July 1, 2006, the market was opened for customers with consumption greater than 9 GWh, which signified the possibility of choosing electricity suppliers for approximately a hundred entrepreneurs, who in the year 2006 consumed approximately a billion kWh of electrical energy,
— on July 1, 2007, the market was opened for all customer categories of entrepreneurs, i.e. for over 200 000 customers, whose consumption in the year 2006 amounted to 8,5 billion kWh of electrical energy or 57 % of total consumption,
— on July 1, 2008, household customers obtained the status of preferred customers, which meant all the electricity customers in Croatia.

In the new legislation, a certain lack of clarity and shortcomings were noted that can create difficulties in the implementation of the law, which could result in a delay in the restructuring and liberalization of the electricity market.

dobno donošenje svih podzakonskih akata, što je privedeno kraju u 2007. godini.

Svi navedeni propisi zajedno definiraju organizaciju elektroenergetskog sektora, položaj pojedih dijelova sektora, model i organizaciju tržišta električne energije, pravila rada i ponašanja i odnose među akterima.

3.7.2 Organizacijsko restrukturiranje HEP-a

Paralelno s prilagodbom hrvatskih energetskih zakona europskim normama, kao dio opće reforme energetskog sektora, započeo je i proces restrukturiranja HEP-a. Taj proces determiniran je, s jedne strane pravno-institucijskim zahtjevima, koji proizlaze iz paketa hrvatskih energetskih zakona i s druge strane specifičnostima povijesnog naslijeđa, odnosno sadašnjeg stanja razvijenosti elektroenergetskog sektora u Hrvatskoj.

Od 2002-07-01 HEP je formalno preoblikovan u HEP Grupu, koju čine: vladajuće društvo Hrvatska elektroprivreda d.d. i ovisna društva s ograničenom odgovornošću. Vladajuće društvo HEP Grupe, HEP Matica, izvedeno je iz dotadašnjeg HEP-a i zadržalo statusno pravni oblik dioničkog društva. HEP d.d. nije promijenio pravni oblik nego samo sadržaj svojeg funkcioniranja. Ovisna društva čiji je osnivač i jedini vlasnik HEP d.d. osnovana su kao trgovačka društva s ograničenom odgovornošću, zbog jednostavnijeg upravljanja.

Nastankom koncerna u HEP Grupi postupno se stvaraju novi statusno pravni i ugovorni odnosi koji omogućuju funkcionalnu povezanost između pojedinih dijelova koncerna i integraciju poslovnih funkcija na razini vladajućeg društva.

Strateški gledano, izabran je takav model restrukturiranja koji bi trebao omogućiti optimiranje ekonomskih tokova, ali i interesa svih interesnih skupina (engl. *stakeholdera*). Zadovoljena je i zadnja Direktiva EU 2003/54/EC, koja zahtijeva razdvajanje djelatnosti, ali ne i razdvajanje vlasništva.

S obzirom na cilj povećanja efikasnosti poslovanja, uz decentralizaciju odlučivanja, kao logično rješenje nametnula se organizacija HEP Grupe prema modelu centara odgovornosti. Svrha formiranja centara odgovornosti je efikasnija kontrola troškova, prihoda i profita i razvijanje tržišnog ponašanja na nižim razinama menedžmenta, odnosno krajnji cilj je povećanje ekonomske djelotvornosti HEP-a. To znači decentralizaciju prava na odlučivanje, decentralizaciju informacija i odgovornosti. Centri odgovornosti su paralelno i objekti i subjekti kontrolnog procesa menedžmenta.

In order to implement reforms with the fewest possible problems and achieve the charted dynamics for the opening of the electricity market, it would be necessary to adopt all the secondary legislation, which was completed in late 2007.

All the cited provisions together define the organization of the electrical power sector, the positions of the individual parts of the sector, the model and organization of electricity markets, rules for work and behavior, and the relations among the actors.

3.7.2 The organizational restructuring of HEP

Parallel to the adaptation of Croatian energy legislation to European standards, the process of the restructuring of HEP has begun as part of the general reform of the energy sector. This process is determined, from the one side, by legal-institutional requirements which ensue from the package of Croatian energy legislation and, from the other side, by the specific characteristics of the historical legacy, i.e. the present state of the development of the electrical power sector in Croatia.

As of July 1, 2002, HEP was formally reformed as the HEP Group, which consists of the following: the governing company of Hrvatska elektroprivreda d.d. and subsidiary companies with limited liability. The governing company of the HEP Group, HEP Headquarters (HEP Matica), was formed from the former HEP and has retained the status of the legal form of a joint stock company. HEP d.d. did not change its legal form but only the content of its function. The subsidiary companies, whose founder and sole owner is HEP d.d., were established as limited liability companies for the purpose of simplifying administration.

With the formation of the HEP Group, new legal status and contractual relations are gradually being created that facilitate the functional connection among the individual parts of the concern and the integration of the business functions at the level of the governing company.

From the strategic viewpoint, a restructuring model has been chosen that should facilitate the optimizing of economic flows but also the interests of all the stakeholders. The current requirements of Directive 2003/54/EC of the European Union have been met, which stipulate the unbundling of activities but not the unbundling of ownership.

Regarding the goal of increasing the efficiency of operations with the decentralization of decision making, it was a logical decision to organize the HEP Group according to the model of centers of responsibility. The purpose of the formation of centers of responsibility is to increase the efficiency of the control of costs, revenues and profits, and the development of market behavior at the lower levels of management, i.e. the ultimate goal is to increase HEP's economic

Organizacija HEP Grupe prema modelu centara odgovornosti znači povećanje ekonomske djelotvornosti inkorporacijom tržišne u hijerarhijsku paradigmu, koja se temelji na decentralizaciji prava na odlučivanje i uspostavi ekonomskih odnosa između centara odgovornosti. Ti odnosi imaju određene karakteristike tržišnog ponašanja, ali su koordinirani i kontrolirani od vladajućeg društva.

Tako su stvorene pretpostavke da organizacijska struktura HEP-a postane prilagodljiva zahtjevima okoline, projektno i inovacijski orijentirana.

4 REGULACIJA JE I DALJE POTREBNA

4.1 Uvod

I nakon restrukturiranja elektroenergetskog sektora djelatnosti prijenosa električne energije, distribucije električne energije i vođenja sustava imaju i dalje karakter prirodnog monopola. To znači da u tim djelatnostima konkurencija nije provediva, barem za sada. Uvođenje konkurencije zahtijeva odvajanje konkurencijskih od još uvijek reguliranih funkcija.

U industrijama prirodnog monopola potrebna je regulacija, ako se želi postići ekonomska učinkovitost. U tim industrijama, najveće tvrtke mogu dati najniže cijene, te tako istjerati suparnike s tržišta. Tvrtka koja ostaje bez konkurencije može određivati monopolističke cijene, smanjujući količinu i djelujući na društvenu dobrobit. Radi sprječavaja takvog ekonomski štetnog ponašanja monopolista i radi strateškog značenja javnih usluga koje oni pružaju u pogledu razvoja i nacionalne sigurnosti, na današnjem stupnju razvoja regulacija se jednostavno nameće kao ekonomska nužnost.

Regulatorski proces predstavlja uravnoteženje prava i odgovornosti reguliranog subjekta u kojem se ekonomska moć reguliranog subjekta uravnotežuje pomoću regulatorske moći regulatorske agencije. Iako različita shvaćanja prate različite sustave, većina ih se pouzdaje u sistem provjere i ravnoteže kako bi bili sigurni da jedna strana u regulatorskom procesu ne može dominirati nad ostalima.

Zbog važnosti uravnoteženja moći reguliranog subjekta i regulatora, nužno je osigurati neovisnost između:

— regulatora i ostalih dijelova vlasti kako bi se smanjio politički utjecaj na odluke regulatora i

efficiency. This means the decentralization of decision-making rights, information and responsibilities. The centers of responsibility are both objects and subjects of the management control process.

The organization of the HEP Group according to the centers of responsibility model signifies the increasing of economic efficiency through the incorporation of the market paradigm into the hierarchical paradigm, which is based on the decentralization of decision-making rights and establishes economic relations among the centers of responsibility. These relations have specific characteristics of market behavior but are also coordinated and controlled by the governing company.

Thus, the prerequisites have been created for the organizational structure of HEP to become adaptable to the requirements of the environment and oriented to projects and innovation.

4 REGULATION IS STILL NECESSARY

4.1 Introduction

Even after the restructuring of the electrical power sector, the activities of the transmission of electricity, distribution of electricity and system control continue to have the character of natural monopolies. This means that competition is not feasible in these activities, at least for the present. The introduction of competition requires the separation of competitive functions from functions that are still regulated.

In industries where there are natural monopolies, regulation is necessary if the achievement of economic efficiency is desired. In these industries, the largest companies can offer the lowest prices and thus drive rivals from the market. A company that is left without competition can set monopolistic prices, reduce quantities and act in a manner that is contrary to the common good. In order to prevent such economically detrimental behavior by monopolists and due to the strategic significance of the public services that they provide in regard to development and national security, regulation at today's level of development has become an economic necessity.

The regulatory process represents the balancing of the rights and responsibilities of the regulated subject in which the economic power of the regulated subject is balanced with the help of the regulatory power of the regulatory agency. Although various systems have various concepts, the majority of them rely on the system of checks and balances in order to insure that one party in the regulatory process cannot dominate the others.

— regulatora i reguliranog subjekta kako bi se smanjila mogućnost maksimaliziranja dobiti na račun potrošača.

Važnost neovisnosti je tako velika da mnoge države donose zakone o sukobu interesa vezane za ekonomsku regulaciju.

4.2 Ciljevi i zadaci regulacije

Iako se ciljevi regulatora razlikuju u raznim zemljama i sektorima, njihov primarni cilj je zaštita kratkoročnih i dugoročnih interesa potrošača povećanjem ekonomske učinkovitosti.

Primarni kratkoročni cilj regulatora električne energije je određivanje tarifne strukture koja reguliranom subjektu omogućuje ostvarenje potrebnih prihoda za pokriće troškova poslovanja i razumnu ratu povrata.

Primarni dugoročni cilj regulatora električne energije je poticanje reguliranog subjekta da stvori dovoljno prijenosnih i distribucijskih kapaciteta potrebnih za podmirenje ukupne potražnje.

Ako regulirani subjekt ima razumnu zaradu od ulaganja, trebao bi postojati odgovarajući poticaj za izgradnjom novih kapaciteta. Ako regulirani subjekt ostvaruje stopu povrata za investiciju koja je viša od normalne, dobiva poticaj da gradi više kapaciteta nego što je to potrebno. Zbog tog problema regulator u principu izdaje neku vrstu dozvole za izgradnju novih kapaciteta, da bi se utvrdilo jesu li novi kapaciteti razuman korak. Neki put to od regulatora u planiranju integriranih (ili najjeftinijih) resursa (*IRP*– *Integrated Resource Planning*) traži da odredi hoće li tehnologija ili sustav koji je predložen donijeti najmanje potrebne prihode. *IRP* određuje najjeftinije planove širenja, tj. uravnoteženu mješavinu proizvodnih jedinica te prijenosnih i distribucijskih postrojenja, uklapajući krajnje akcije na strani potražnje [23]. Ta potreba povećava troškove regulacije, pa se proračun troška u odnosu na dobit mora napraviti prije uključenja regulatora u tu aktivnost. Taj se postupak može povjeriti i drugom regulatoru, povećavajući kontrolu i ravnotežu u regulatorskom sustavu.

Zadatak regulacije je poticanje ulaganja do te mjere koja će biti dovoljna za ispunjenje zahtjeva potrošača i za povrat razumne svote uloženog novca ulagačima. Budući da se elektroenergetski sektor restrukturira, posao regulatora postaje određivanje tržišnih pravila koja će dovesti do konkurencijskih uvjeta u kojima će cijene i količine biti slične onima u uvjetima prave konkurencije. Ekonomska regulacija u mrežnim djelatnostima označava radnje ko-

Due to the importance of balancing the power of the regulated subject and regulator, it is necessary to insure independence among the following:

— the regulator and other parts of the authorities, in order to reduce political influence on the decisions of the regulator and
— the regulator and the regulated subject, in order to reduce the possibility of maximizing profits at consumer expense.

The importance of independence is so great that many countries adopt legislation on conflict of interests in connection with economic regulation.

4.2 The goals and tasks of regulation

Although the goals of regulators differ in various countries and sectors, the primary goal is the protection of the short-term and long-term interests of the consumer by increasing economic efficiency.

The primary short-term goal of the regulator of electrical power is to determine the tariff structure that makes it possible for a regulated subject to obtain the necessary revenues in order to cover operational costs and a reasonable rate of return.

The primary long-term goal of the regulator of electrical power is to stimulate the regulated subject to create sufficient transmission and distribution capacities to cover total demand.

If a regulated subject has reasonable earnings from investment, there should be suitable incentive for the construction of new generating capacities. If a regulated subject is obtaining a rate of return on investment that is higher than normal, it has an incentive to build more capacities than necessary. Due to this problem, in principle the regulator issues a type of permit for the construction of new capacities in order to determine whether these new capacities are a reasonable step. Sometimes in integrated resource planning (*IRP*), the regulator is required to determine whether a proposed technology or system will bring in the minimum necessary revenues. Integrated resource planning determines the least expensive expansion plans, i.e. a balanced mixture of production units and transmission and distribution installations, and integrated demand side actions [23]. This requirement increases regulation costs, so that the cost-benefit ratio must be calculated before the regulator becomes involved in this activity. This procedure can be entrusted to another regulator, thereby increasing control and balance within the regulatory system.

The task of regulation is to stimulate investment to the extent that will be sufficient for meeting the demands of consumers and for the return of a reasonable amount on investments to investors. Since the electrical power sector is being restructured, the jima se operatorima mrežnih sustava na neki način ograničavaju cijene, prihodi, stopa povrata i operativni i kapitalni troškovi [24]. Regulacija se suočava s problemom iznalaženja ravnoteže između optimalnog korištenja postojećih kapaciteta i optimalnog povećanja kapaciteta. Utvrđivanje transparentne i na troškovima utemeljene tarife za korištenje mreže jedan je od preduvjeta za uklanjanje zapreka uvođenju konkurencije na tržište električne energije, poglavito ukoliko se radi o elektroenergetskom poduzeću koje obavlja i regulirane (prijenos i distribucija električne energije te vođenje elektroenergetskog sustava) i tržišne (proizvodnja i opskrba električnom energijom) djelatnosti. Tarife za korištenje mreže koje ne odražavaju ekonomske troškove izazivaju neučinkovitost i distorzije u razvoju prijenosnog i distribucijskog sustava.

Nužni preduvjet za uvođenje transparentne metodologije za izračun tarifa je provođenje razdvajanja djelatnosti unutar poduzeća koje obavlja i regulirane i tržišne djelatnosti. Direktiva 2003/54/EC nalaže da integrirana elektroenergetska poduzeća vode odvojeno računovodstvo za svaku pojedinu djelatnost, te da se na taj način svakoj od djelatnosti dodjeljuju samo troškovi koji su vezani za tu djelatnost. Zbog toga je računovodstveno razdvajanje djelatnosti bitni element regulacije, bez kojeg regulatorno tijelo ne može spriječiti unakrsne subvencije među različitim dijelovima integriranog elektroenergetskog poduzeća.

Važna zadaća regulacije je kontrola ulaza i izlaza iz sektora, što se regulira pomoću pravila pristupa. Kod konkurencije stvarni ili mogući ulaz konkurentskih ponuđača smanjuje tržišnu moć poduzeća u sektoru. Regulacija električne energije uključuje ugovor koji reguliranom subjektu daje ekskluzivno pravo za obavljanje određene djelatnosti u zamjenu za podvrgavanje regulatorskoj kontroli. Međutim, proizvodnja električne energije može biti nusproizvod industrijskog procesa (koproizvodnja) i bilo bi društveno neučinkovito da se mogući višak električne energije iz tih industrija ne distribuira. Zato regulator mora odlučiti tko može prodavati električnu energiju ekskluzivnom distributeru i po kojoj cijeni. Što se tiče izlaza, taj se problem ne pojavljuje na isti način kao kad tvrtke izlaze iz konkurencijskih tržišta. Ako tvrtka bankrotira regulator mora naći novog vlasnika imovine i koncesije.

4.3 Regulacijska iskustva SAD-a

U SAD-u postoji duga tradicija ekonomske regulacije. Još od početka dvadesetog stoljeća nad tvrtkama koje pružaju javne usluge provodi

task of the regulator has become the determination of market rules that will lead to competitive conditions in which prices and quantities will be similar to those under the conditions of genuine competition. Economic regulation in network activities refers the means by which limitations are established for network system operators regarding prices, revenues, rate of return, and operating and capital costs [24]. Regulation encounters the problem of finding a balance between the optimal use of existing generating capacity and the optimal increase of capacity. The determination of transparent and cost-based tariffs for using a network is one of the prerequisites for eliminating obstacles to the introduction of competition on the electricity market, particularly insofar as this concerns an electrical power company that also performs regulation (the transmission and distribution of electricity and the management of the electrical power system) and market activities (production and supply of electricity). Tariffs for using a network that do not reflect the economic costs lead to inefficiency and distortion in the development of transmission and distribution systems.

An essential prerequisite for the introduction of transparent methodology for the calculation of tariffs is the implementation of unbundling within enterprises that perform both regulatory and market activities. Directive 2003/54/EC states that an integrated electricity enterprise should have separate accounting for each individual activity, in order for each activity to be assigned only the costs that it incurs. Therefore, unbundling activities in accounting is an essential element of regulation, without which a regulatory body cannot prevent cross subsidies among various parts of an integrated electrical power enterprise.

An important task of regulation is control of entering and exiting the sector, which is regulated by means of access rules. With competition, an actual or possible entrance of a competitive bidder reduces the market power of the companies in the sector. The regulation of electricity includes a contract by which the regulated subject is given the exclusive right to perform certain activities in exchange for submission to regulatory control. However, the production of electricity can be a by-product of an industrial process (coproduction) and it would be socially inefficient not to distribute eventual surplus energy from these industries. Therefore, the regulator must decide who can sell electricity to the exclusive distributor and at what price. Regarding exit, that problem does not occur in the same manner as when companies leave competitive markets. If a company is bankrupt, the regulator must find a new owner for the property and concession.

4.3 The regulatory experience of the United tates

In the United States, there is a long tradition of economic regulation. Since the beginning of the twense regulacija, tako da se može konstatirati da svjetski proces regulacije javnih usluga ima svoje korijene upravo u SAD-u. Današnji je princip da savezne države u SAD-u imaju neovisna regulatorna tijela [25]. U energetskom sektoru regulacije prisutna je velika različitost, jer reforma još nije izvršena u svim saveznim državama.

Posebna pozornost posvećuje se neovisnosti regulatornog tijela, do te mjere da regulatorsko djelovanje može nalikovati na sudsko saslušanje. Npr., u Kaliforniji, zbog složenosti reguliranja, saslušanja obično provode imenovani suci upravnog prava koji daju preporuke na temelju dokaza koje podnosi regulatorsko osoblje, regulirani subjekt i ostale zainteresirane strane. Takva sudska orijentacija vodi donošenju odluka od slučaja do slučaja. Svi ti postupci traju i stvaraju društveni trošak. Da bi se smanjio društveni trošak regulacije, regulirana tvrtka ima pravo na pravodobnost procesa, tj. regulatorska agencija i sudski sustav moraju poštivati sudske rokove. S druge strane, zbog toga što regulirani subjekti mogu smišljeno manipulirati regulatorskim procesom (odugovlačeći s davanjem informacija regulatoru), i oni se moraju držati rokova i procedura, ili bivaju kažnjeni.

U praksi, regulacija u SAD-u dobiva tipičnu prolaznu ocjenu, a mogla bi biti i puno bolja da se napori koji se čine u deregulaciji okrenu poboljšanju regulacije [3].

4.5 Neki problemi regulacije

Ključni regulacijski problem koji se tiče djelovanja sustava je kako održati pouzdano djelovanje u podijeljenoj strukturi. Regulirana i vertikalno integrirana poduzeća su dobrovoljno surađivala kako bi omogućili djelovanje pouzdanog sustava koordinacijom svojih resursa sa resursima susjednih poduzeća, znajući da će regulirane tarife pokriti zajedničke troškove. Kod deregulacije, operator sustava je odgovoran za njegovu pouzdanost. On kupuje razne pomoćne usluge od proizvođača i potrošača kako bi održao sustav pouzdanim. Međutim, pravne odgovornosti operatora sustava (posebice onih koji ne posjeduju imovinu za prijenos) moraju biti jasno definirane novim pravilima.

S druge strane, prijenosne mreže nisu koncipirane za prijenos električne energije s tržišta električne energije. Kako bi to mogle potrebno je osuvremeniti procedure planiranja prijenosa i definirati odgovornosti ulaganja u prijenos između operatora sustava i vlasnika prijenosa. To posebno vrijedi u slučajevima

tieth century, regulation was imposed over companies that provided public services. Therefore, it can be stated that the world process of the regulation of public services actually has its roots in the United States. The present principle is that the individual states in the USA have their own independent regulatory bodies [25]. In the regulation of the energy sector, there are great differences because reform has still not been completed in each of the states.

Particular attention is devoted to the independence of the regulatory body, to the extent that regulatory activity can resemble a court hearing. For example, in California, due to the complexity of the regulation, a hearing is usually conducted by appointed judges of administrative law who make recommendations on the basis of evidence submitted by the regulatory personnel, regulated subject and other stakeholders. Such a judicial orientation leads to decision making from case to case. All these procedures take time and incur public expenses. In order to reduce the public expenses of regulation, the regulated company has the right to a timely process, i.e. the regulatory agency and the court system must respect court deadlines. From the other side, since regulated subjects can manipulate the regulatory process in a premeditated manner (delaying giving information to the regulator), they must also respect the deadlines and procedure, or be punished.

In practice, regulation in the United States receives a typically passing grade. It could be much better if the efforts made in deregulation were directed toward improving regulation [3].

4.5 Some regulatory problems

A key regulatory problem regarding the activity of a system is how to maintain reliable activity in a divided structure. Regulated and vertically integrated enterprises have voluntarily cooperated in order to facilitate the operation of a reliable system through the coordination of their resources with the resources of neighboring enterprises, in the knowledge that the regulated tariffs will cover joint expenses. In deregulation, the operator of a system is responsible for its reliability. He purchases various auxiliary services from producers and consumers in order to maintain the reliability of the system. However, the legal liability of system operators (particularly those who do not possess property for transmission) must be clearly defined by new rules.

From the other side, transmission networks were not conceived for the transmission of electricity from the electricity market. In order for them to do so, it would be necessary to modernize the procedures for the planning of transmission and define the responsibilities for investment in transmission between the system operator and the owner of transmission. This is particularly the case when these functions are u kojima su te funkcije odvojene. Nadalje, sustavi s problemima zagušenja u prijenosu koriste lokacijske cijene kao mehanizam kojim sudionicima na tržištu šalju prave ekonomske signale za korištenje zagušenih puteva. U tom smislu, sudionici na tržištu mogu poticati ulaganja u mrežu prema uočenoj ekonomskoj vrijednosti.

U regulatorskom režimu koji određuje prihod industriji s imovinom koja ima dugi vijek trajanja, kredibilitet regulatorskih obveza je vrlo važan. Prije no što će odrediti sredstva za investicije, ulagače treba uvjeriti da će regulator dozvoliti buduće prihode koji će jamčiti povrat troškova. Regulator mora imati na umu i kratkoročne interese potrošača u vidu jeftine i kvalitetne usluge, i njihove dugoročne interese u vidu sigurne i pouzdane isporuke električne energije u budućnosti.

Uvođenje konkurencije u veleprodaju i maloprodaju zahtijeva, gledano ukupno, znatno veću regulaciju svih elektroenergetskih djelatnosti u odnosu na vrijeme regulacije, s jedne strane radi osiguranja potrebnih uvjeta za funkcioniranje tržišta, i s druge strane radi zaštite potrošača, u smislu kvalitete i dugoročne sigurnosti opskrbe električnom energijom, tako da bi umjesto o deregulaciji bilo ispravnije govoriti o novoj regulaciji.

Čini se da ekonomika prirodnih monopola, tržišta i regulacije nije dovoljna za razumijevanje složenosti nužnih regulatorskih procesa. Postoje mnogi problemi praktične naravi koji bi se trebali istražiti na proučavanju konkretnih primjera, kako bi se postiglo bolje razumijevanje složenosti reforme elektroenergetskog sektora.

5 PROBLEMI I EFEKTI LIBERALIZACIJE TRŽIŠTA ELEKTRIČNE ENERGIJE

5.1 Problemi liberalizacije tržišta električne energije

Električna energija predstavlja specifičnu robu. Potroši se unutar jedne desetine sekunde nakon proizvodnje, a manje od jedne desetine sekunde se može pohraniti kao električna energija u sustavu. Ova fizikalna svojstva stvaraju proizvod čiji se krajnji troškovi proizvodnje ubrzano mijenjaju, a zbog toga se brzo mijenjaju i toškovi kod isporuke. Troškovi isporuke se ne mijenjaju ni približno tako brzo ni kod jednog drugog proizvoda.

separate. Furthermore, systems with congestion problems in transmission use the local prices as a mechanism by which market participants send genuine economic signals for the use of congested lines. In this sense, market participants can stimulate investment in the network according to the assessed economic value.

In a regulatory regime that determines the revenues of the industry from property with a long lifetime, the credibility of the regulatory obligations is very important. Before determining the assets for investment, investors must be convinced that the regulator will permit future revenues that will guarantee a return of expenditures. The regulator must also bear in mind the short-term interests of customers regarding inexpensive and quality services, together with their long-term interests regarding the secure and reliable delivery of electrical energy in the future.

The introduction of competition in wholesale and retail, viewed together, requires significantly greater regulation of all electricity activities regarding the period of regulation, from the one side for the purpose of securing the necessary prerequisites for the functioning of the market and from the other side for consumer protection in the sense of the quality and long-term security of the electricity supply. Therefore, instead of deregulation it would be more correct to speak of new regulation.

It appears that the economics of natural monopolies, markets and regulations is not sufficient for understanding the complexity of the necessary regulatory processes. There are many problems of a practical nature that should be investigated by studying concrete examples, in order to achieve better understanding of the complexities of the reform of the electrical energy sector.

5 PROBLEMS AND EFFECTS OF THE LIBERALIZATION OF THE ELECTRICITY MARKET

5.1 Problems of the liberalization of the electricity market

Electrical energy represents a specific good. It is consumed within a tenth of a second after it is produced, and less than a tenth of a second can be stored as electrical energy in a system. These physical properties create a product whose final production costs fluctuate rapidly, and therefore delivery costs also fluctuate rapidly. Delivery costs do not fluctuate nearly as much for any other product.

There are several fundamental problems in the deregulation of electricity:

Postoji nekoliko bitnih problema u deregulaciji električne energije:

— složenost elektroenergetskog sustava,
— lokalna tržišna moć i
— nedostaci na strani potražnje električne energije:
    · nedostatak mjerenja i obračuna prema stvarnoj potrošnji i
    · nedostatak kontrole stvarne potrošnje energije kod pojedinačnih potrošača.

Elektroenergetski sustav je delikatan, jedinstven sustav, koji se prostire, u pravilu, na području cijele države. Svi proizvođači u sustavu moraju djelovati sinhronizirano do u sekundu. Napon se mora održavati unutar 5 % ograničenja, na velikom broju odvojenih lokacija. To se mora ostvariti na zajedničkom postrojenju, od kojeg polovica (mreža) mora funkcionirati zbog općeg dobra, a druga polovica (proizvođači i opskrbljivači) funkcionira zbog različitih privatnih interesa.

Složenost se može prevladati dovoljno dobro osmišljenim paketom tržišnih pravila, ali se problem lokalne tžišne moći mora, barem za sada, rješavati intervencionističkim mjerama. Do sada je to uspješno rađeno. Npr., više od polovice proizvođača u Kaliforniji je dobilo oznaku mora raditi, jer su u određenom trenutku tijekom godine ključni za funkcioniranje sustava. Zbog toga imaju golemu tržišnu moć te nije bilo druge mogućnosti nego im regulirati cijenu. San Francisco i New York su, uz ostale gradove, džepovi potrošnje, jer potrebuju više električne energije nego mogu uvesti. Kao posljedica toga, dva proizvođača u San Franciscu bi, da nisu regulirani, imala golemu tržišnu moć za vrijeme sati maksimalne potrošnje svakog dana. Ti su proizvođači potrebni zbog svoje stvarne proizvodnje električne energije, ali većina njih s oznakom mora raditi je potrebna zbog svoje reaktivne energije [3]. U takvim situacijama postavlja se pitanje što je od tržišta električne energije ostalo, pogotovo tamo gdje se reguliranje cijene odnosi na većinu proizvođača.

Iako je mjerenje stvarne potrošnje počelo u kasnim 1980-im godinama, ono je prekinuto za potrošače u kućanstvima, a i gotovo nijedan potrošač u gospodarstvu ne vidi cijene stvarne potrošnje. Kao posljedica toga, gotovo nitko od potrošača ne reagira na promjene u troškovima isporučene energije. Znači, prvi nedostatak na strani potražnje uzrokuje pomanjkanje reagiranja potražnje na cijenu odnosno pomanjkanje elastičnosti potražnje.
Uz ovaj nedostatak, tržište bi moglo funkcionirati u skladu s ekonomskim principima, ali tu je i drugi nedostatak na strani potražnje –

— the complexity of the electrical power system,
— local market power and
— shortcomings on the demand side of electricity:
    · the lack of metering and billing according to actual consumption and
    · the lack of the control of the actual energy consumption of individual customers.

The electrical power system is a delicate integral system that extends, as a rule, throughout the territory of an entire country. All the producers within the system must operate synchronously within a fraction of a second. Voltage must be maintained within a 5 % limit at a large number of separate locations. This must be achieved in a shared system, of which half (the network) must function for the general good and the other half (producers and suppliers) are motivated by various private interests.

The complexity can be overcome with a sufficiently well thought out package of market regulations but the problem of local market power must, at least for the present, be solved through measures of intervention. Until now, this has been successful. For example, over half the producers in California are designated as must run because at a specific moment during the year they are crucial for the function of the system. Therefore, they have enormous market power and there was no other option except to regulate their prices. San Francisco and New York, in addition to other cities, are pockets of consumption because they require more energy than they can bring in. As a consequence, two producers in San Francisco would have, if they were not regulated, enormous market power at the time of maximum consumption every day. These producers are necessary due to their actual electricity production but the majority of them designated as must run are necessary due to their reactive power [3]. Under such situations, the question is asked what has remained of the electricity markets, especially where price regulation affects the majority of producers.

Although the metering of actual consumption began in the late 1980s, this was discontinued for household customers. Therefore, almost no household customers see the price of actual consumption. As a consequence, nearly no customers react to changes in the costs of delivered energy. This shortcoming on the demand side leads to a lack of reaction to price on the demand side, i.e. a lack of elasticity of demand.

In addition to this shortcoming, the market should be able to function in compliance with economic principles but there is another shortcoming on the demand side – the option for customers to take energy from the network without entering into a prior agreement with the producer [26]. If it were possible to implement bilateral contracts with the physical disconnection of customers who violate the contracted terms, the market would be able to function in compliance with mogućnost potrošača da uzme energiju iz mreže bez prethodnog dogovora s proizvođačem [26]. Kad bi se dvostrani ugovori mogli provoditi fizičkim isključivanjem potrošača koji prekrše ugovor, tržište bi moglo funkcionirati u skladu s teorijom konkurencijskih tržišta. Ni na jednom drugom tržištu nije nemoguće fizički osigurati provođenje dvostranih ugovora na temelju vremenske ljestvice promjene cijena. Dakle, drugi nedostatak na strani potražnje sprječava fizičko provođenje dvostranih ugovora i uzrokuje to da je u određenom vremenskom periodu operator sustava istodobno i nemarni opskrbljivač.

Zbog činjenice da je reakcija potražnje na cijenu minimalna, može se dogoditi da se krivulje ponude i potražnje ne križaju, a to je toliko velika mana tržišta da je ne promišlja nijedan tekst s područja ekonomije. Operator sustava prisiljen je određivati cijenu barem onda kad ponuda ne zadovoljava potražnju. Trenutačno, sva tržišta električne energije funkcioniraju na taj način i to će se nastaviti sve dok se vrlo slaba elastičnost potražnje ne ojača.

To nisu samo teoretski problemi, već veliki nedostaci funkcioniranja tržišta električne energije u praksi, jer dovode do krajnje neprihvatljivih odnosa troškova proizvodnje i cijena električne energije na tržištima**.** Dok je prosječni trošak proizvodnje oko 35 USD/MWh, a maksimalni trošak s novom opremom 100 USD/MWh, cijene na mnogim tržištima se kreću od
1 000 USD/MWh do 10 000 USD/MWh. Upravo zbog toga sva četiri tržišta u SAD-u imaju formalne limite na cijene. Uz krajnju neelastičnost potražnje koju uzrokuje prvi nedostatak, sama nestašica bi prouzročila visoke cijene, ali potražnja sa nedostatcima udružena s nestašicom proizvodi idealne uvjete za stvaranje tržišne moći koja još diže cijene [27].

Nakon deset godina postojanja, britansko se tržište proglasilo neuspješnim i promijenilo sva svoja tržišna pravila. Kalifornijsko tržište je u samo jednoj godini uspjelo svojim korisnicima donijeti trošak veći od priželjkivane desetogodišnje uštede. U New Yorku su cijene narasle do vrtoglavih 6 000 USD/MWh u 2000. godini, a u Novoj Engleskoj je tvrtka morala zatvoriti svoje izgrađene kapacitete zbog golemih problema s tržišnom moći [3]. Kolosalna i nezamjenjiva uloga elketrične energije, kako u životu općenito, tako i u gospodarstvu, usmjerava sve zemlje da nastoje svoje potrebe za električnom energijom zadovoljiti uz što manju ovisnost o uvozu, što predstavlja značajan ograničavajući faktor razvoja efikasnog veleprodajnog konkurencijskog tržišta.

the theory of market competition. It is not impossible on any other market to guarantee the physical implementation of bilateral contracts on the basis of the changes in price according to a time scale. Thus, this second shortcoming of the demand side prevents the physical implementation of bilateral contracts, with the result that within a specific period of time the system operator is also a negligent supplier.

Due to the fact that the reaction by demand to price is minimal, it can happen that the curves of supply and demand do not intersect. This is such a great market shortcoming that such a case is not even analyzed in any economics texts. The system operator is forced to determine price, at least when supply does not meet demand. Currently, all electricity markets are functioning in this manner and will continue to do so as long as the elasticity of demand remains weak.

These are not merely theoretical problems but great shortcomings in the functioning of the electricity markets in practice, because they lead to extremely unacceptable ratios between production costs and the prices of electricity on the markets. While the average cost of production is approximately 35 USD/MWh, and the maximum cost with new equipment is 100 USD/MWh, prices on many markets range from 1 000 USD/MWh to 10 000 USD/MWh. It is precisely for this reason that all the four markets in the United States have formal price caps. In addition to the extreme inelasticity of demand caused by the first shortcoming, shortages themselves would cause high prices. However, demand together with these shortcomings combined with shortages would lead to the ideal conditions for creating market power that would further raise prices [27].

After ten years of existence, the British market declared failure and changed all its market regulations. In only one year, the California market succeeded in incurring expenses for its customers that exceeded the savings that had been hoped for over a ten-year period. In New York, the prices rose to a dizzying 6 000 USD/MWh in the year 2000, and in New England a company had to close its construction facilities due to enormous problems with market power [3]. The colossal and irreplaceable role of electrical power, both in general life and in the economy, requires all countries to attempt to meet their electricity needs with as little dependence upon imports as possible, which represents a significantly limiting factor for the development of an efficient competitive wholesale market.

In the processes of creating a competitive atmosphere in the electrical power sector, there is also increasing recognition of the social significance of electricity supply services in the security of supply, environmental protection, protection of vulnerable consumers in respect to the regularity of supply, the quality of supply and the prices of electricity deliv-

I u procesima stvaranja konkurencijskog okruženja u elektroenergetskom sektoru sve više se ponovo prepoznaje javni značaj elektroprivrednih usluga i to u sigurnosti opskrbe, zaštiti okoliša i zaštiti ugroženih potrošača u pogledu redovitosti opskrbe, kvalitete opskrbe, ali i cijene isporučene električne energije. Sve to znači redukciju slobodnog tržišta, prvenstveno u maloprodaji. To posebno dolazi do izražaja u formiranju unutrašnjeg tržišta električne energije u EU, gdje se u novoj direktivi 2003/54/EC u odnosu na prethodnu jača institut obveze javne usluge, a sve radi bolje zaštite potrošača, odnosno zaštite općeg ekonomskog interesa.

Iako su ovi problemi i nedostaci ozbiljni, oni ipak ne znače da je liberalizacija osuđena na propast, jer neka tržišta dosta dobro funkcioniraju. S vremenom bi potražnja na tržištu trebala razviti dovoljno elastičnosti u pogledu cijena. Ta se promjena u strukturi tržišta treba poticati od početka. Odgovorna deregulacija elekrične energije treba najprije popraviti nedostatke u potražnji, a onda pokrenuti tržište. Jeftinije je ispraviti njih, nego probleme koje su već prouzročili.

Najteži i najskuplji problemi novih tržišta električne energije se uglavnom tiču tržišne strukture. Kad to bude osviješteno, te kad se zaista suočimo s nedostacima na strani potražnje i problemima tržišne moći i prijenosa, vjerojatno će se naći odgovarajuća rješenja.

5.2 Procjena odnosa troškova i koristi od liberalizacije tržišta električne energije

U tijeku je intenzivan svjetski proces reforme industrije električne energije. S obzirom na činjenicu da reformatori vrlo često krivo procjene rezultate svojih reformi, veliko je pitanje, promatrano globalno, jesu li veći ukupni društveni troškovi ili ukupne društvene koristi od danas prakticirane deregulacije, odnosno liberalizacije tržišta električne energije.

Troškovi liberalizacije tržišta električne energije iz današnje perspektive su:

- izgradnja prijenosnih kapaciteta za potrebe trgovanja električnom energijom,
- gubici u gospodarstvu i društvu, uzrokovani raspadom elektroenergetskih sustava i redukcijama isporuke, nastali kao posljedica liberalizacije,
- znatno veća regulativa u elektroenergetskom sustavu nego što je to bilo prije liberalizacije,
- samo donošenje, a još više implementacija i provođenje svih tih novih regula stvara

ered. All of this signifies reduction of the free market, primarily in retail. This becomes particularly apparent in the formation of the internal electricity market of the European Union, where in the new Directive 2003/54/EC in comparison to the previous one, the responsibilities of public services have increased, all for the purpose of providing better consumer protection, i.e. the protection of general economic interests.

Although all these problems and shortcomings are serious, they nonetheless do not indicate that liberalization is doomed to failure because some markets are functioning well. With time, market demand would develop sufficient elasticity regarding prices. This change in the market structure should be stimulated from the beginning. Responsible deregulation of electricity should first of all correct the shortcomings in demand, and then the market. It is less expensive to correct these shortcomings than the problems they have already caused.

The most serious and most expensive problems of the new electricity markets generally concern market structure. When we become aware of this and genuinely confront the shortcomings on the demand side and the problems of market power and transmission, we shall probably find the appropriate solutions.

5.2 Assessment of the cost-benefit ratio of the liberalization of electricity markets

An intensive worldwide process for the reform of the electrical power industry is underway. Due to the fact that reformers very frequently incorrectly assess the results of their reforms, it is a great question, considered globally, whether total public costs or benefits are greater from the deregulation being practiced today, i.e. the liberalization of the electricity markets.

The costs of the liberalization of electricity markets from today's perspective are as follows:

- it is necessary to construct transmission capacities for the requirements of electricity commerce,
- there are losses in the economy and society due to the disintegration of the electrical power systems and reduction in deliveries that have occurred as consequences of liberalization,
- there are significantly more regulations in the electrical power system than prior to liberalization,
- only the adoption and, even more so, the implementation of all these new regulations create significant additional costs for the function of an electrical power system,
- the functions of the regulatory bodies, market operator, system operator, exchanges and other market institutions and structures represent

znatne dodatne troškove funkcioniranja elektroenergetskog sustava,
- funkcioniranje regulatornih tijela, operatora tržišta, operatora sustava, burzi i drugih tržišnih institucija i struktura predstavlja velike nove, odnosno prateće troškove rada elektroenergetskog sustava. Samo je budžet regulatornih tijela 26 europskih zemalja (23 članice Europske unije i 3 kandidata za članstvo) u 2003. godini iznosio oko 200 milijuna eura [28]. Regulirana cijena električne energije, ali i slobodno formirana cijena električne energije sadrže i naknadu za obavljanje poslova regulacije energetskih djelatnosti kao i naknadu za obavljanje poslova organizacije tržišta električne energije,
- rastakanje vertikalno integriranih elektroenergetskih tvrtki, sustava koji su izgrađivani desetljećima, razdvajanjem reguliranih od tržišnih djelatnosti, odnosno potpuno razdvajanje (osim vlasničkog) operatora prijenosnog sustava i operatora distribucijskog sustava od ostalih energetskih djelatnosti (razdvajanje računa, pravno, organizacijsko i upravljačko razdvajanje), svakako stvara značajne izvanredne troškove (poslovni prostor, oprema, radnici i dr.),
- mogućnost biranja opskrbljivača za kupce samo na prvi pogled njima znači pogodnost. To kupcima (pogotovo većim i velikim) nameće potrebu istraživanja tržišta, odnosno angažiranje konzultanata i posrednika za sklapanje ugovora, jer je nova regulativa opsežna i složena i predstavlja potpunu nepoznanicu za kupce. To će za kupce značiti dodatne troškove korištenja električne energije, uz veću neizvjesnost u smislu razine cijene. I promjena opskrbljivača izaziva trošak kojeg će plaćati kupci korisnici te usluge, ili solidarno svi kupci. I za male kupce odnosno kućanstva, to znači veći angažman i brigu oko snabdijevanja električnom energijom, a koristi, barem što se tiče manje cijene u odnosu na regulirani sustav, neće biti.

Uz ove direktne troškove liberalizacije tržišta električne energije pojavit će se i indirektni, zbog napornijeg i stresnijeg rada i neizvjesnijeg statusa radnika zaposlenih u elektroenergetskim poduzećima.

Neosporno je da tržište električne energije donosi određene koristi, od kojih su najznačajnije:

- povećanje efikasnosti poslovanja tvrtki u tržišnim djelatnostima, a djelomično i u monopolnim djelatnostima, zbog povećane

great new, i.e. additional costs for the operation of an electrical power system. Only the budget of the regulatory bodies of 26 European countries (23 member states of the European Union and 3 candidates for membership) in the year 2003 amounted to approximately 200 million euros [28],
- regulated electricity prices but also freely formed electricity prices contain compensation for the work performed for the regulation of electrical power activities as well as compensation for the work performed for the organization of the electricity markets.
- the unbundling of vertically integrated electrical power companies, systems that have been built for decades, the unbundling of regulated operations from market operations, i.e. the complete unbundling (except ownership) of the transmission system operator and the distribution system operator from the other energy activities (the unbundling of accounts; legal, organizational and administrative unbundling) certainly create significant extra expenses (office space, equipment, personnel etc.).
- affording customers the option of choosing their suppliers only seems like a benefit to them at first glance. Customers (especially large ones) have to investigate the market, i.e. engage consultants and an agent for entering contracts, because the new regulations are extensive and complex, representing a complete unknown. This also means additional customer outlays for the use of electrical power, together with greater uncertainty regarding the level of prices. Changes in suppliers incur expenses that will be paid for by the customers benefiting from these services or all customers in solidarity. For small customers or households, this necessitates greater engagement regarding the electricity supply. At least in terms of lower prices in relation to the regulated system, there will be no benefits.

In addition to these direct costs of the liberalization of electricity markets, there will also be indirect costs due to the strenuous and stressful work and uncertain status of workers employed by electrical power companies.

It is indisputable that the electricity market brings certain benefits, of which the more significant are as follows:

- increased efficiency of the operations of the company in market operations, and partially also in monopoly operations, due to increased regulation (transmission and distribution) in comparison to the previous period,
- reduced need for the installation of generating capacities while maintaining the same level of system security,
- improved utilization of favorable hydrological conditions and

regulacije (prijenosa i distribucije) u odnosu na ranije razdoblje,
- smanjenje potrebe za instaliranim proizvodnim kapacitetima uz zadržavanje iste razine sigurnosti sustava,
- bolje iskorištavanje povoljnih hidroloških prilika,
- podizanje razine usluge.

Uspoređujući ovako pobrojene troškove i koristi implementacije tržišta u elektroenergetski sektor, teško se može reći da će koristi biti veće od troškova. Čak suprotno, smatramo da će troškovi, u fazi provođenja kompletne reforme elektroenergetskog sustava i implementacije tržišta električne energije znatno nadmašiti koristi. A teško je vjerovati da i nakon uhodavanja tržišta električne energije koristi od uvođenja tržišta mogu nadmašiti njegove sporedne troškove. Kad bi se to i dogodilo trošak električne energije za potrošače sigurno neće biti manji, već samo viši, jer će svi sudionici tržišta, od proizvođača i opskrbljivača do trgovaca, posrednika i brokera, težiti maksimalizaciji svojih zarada. To je već na krajnje neprimjeren i neprihvatljiv način vidljivo na mnogim tržištima.

Čini se da bi bilo globalno daleko efikasnije da se energiju, vrijeme i sredstva utrošena na deregulaciju i liberalizaciju usmjerilo na sigurnost opskrbe, tehnički napredak i ekonomsku učinkovitost elektroenergetskog sustava.

5.3 Efekti liberalizacije tržišta električne energije

Temeljem procjene odnosa troškova i koristi od liberalizacije tržišta električne energije može se reći da liberalizacija neće ostvariti glavni cilj zbog kojeg je pokrenuta, a to je sniženje cijene električne energije. To se dogodilo samo na početku toga procesa u nekim zemljama Europske unije i trajalo je dok je bilo viškova jeftine električne energije u istočnoeuropskim zemljama, odnosno od 1998. do 2002. godine. Od 2003. godine cijene električne energije u Europi imaju uzlazan trend. Sada je svima jasno da su niže cijene električne energije iluzija.

Temeljem ovog nalaza nameće se opravdano pitanje, zbog čega se unatoč raznim kontroverzama i očitim neuspjesima liberalizacije tržišta električne energije (Kalifornija), ipak nesmanjenim intenzitetom nastavlja taj proces? Čini se da odgovor leži u očekivanjima glavnih energetskih subjekata na tom tržištu, koji ipak očekuju dobru zaradu. Očekuju da će uzeti uz svoj dio i dio kolača od mnogih drugih od globalnih koristi liberalizacije tržišta električne energije. Uz to pružaju se i mogućnosti špekulacija na

- improvement in the level of services.

Comparing the aforementioned costs and benefits of the implementation of the market in the electrical power sector, it is difficult to say that the benefits will be greater than the costs. On the contrary, we are of the opinion that the costs in the phase of the implementation of the complete reform of the electrical power system and implementation of the electricity market will significantly exceed benefits. It is difficult to believe that the benefits of the electricity market could exceed its incidental expenses even after it is in full operation. If this were to occur, the price paid by electricity customers will certainly not be lower but only higher, because all market participants, from the producer and supplier to the trader, agent and broker, will tend to maximize their earnings. This is already evident on many markets in an extremely inappropriate and unacceptable manner.

It seems that it would be globally far more efficient for the energy, time and assets spent on deregulation and liberalization to be directed to the security of supply, technical advancement and economic efficiency of the electrical power system.

5.3 The effects of the liberalization of the electrical energy markets

Based upon the estimated cost-benefit ratio from the liberalization of the electrical energy markets, it can be said that liberalization will not achieve the main goal due to which it was initiated, which is the reduction of electricity prices. This only happened at the beginning of the process in some of the countries of the European Union and lasted as long as there were surpluses of cheap electricity in Eastern European countries, i.e. from 1998 to 2002. Since the year 2003, the prices of electrical energy in Europe have shown an upward trend. Now it is clear to all that lower electricity prices are an illusion.

Based upon this finding, it is justifiable to ask why, despite various controversies and obviously unsuccessful liberalization of the electrical power markets (California), the process has continued with undiminished intensity. It appears that the answer lies in the expectations of the major energy subjects on this market, who nonetheless expect good earnings. It is anticipated that in addition to their part of the cake they will take part of the cake from many others due to the global benefits of the liberalization of the electricity markets. Moreover, there are opportunities for speculations on the market, where the large energy subjects are again at an advantage. Since their home countries support them, and these are generally large countries, small countries must simply follow suit.

If regulatory curbs are loosened, quality can come into question but also the security of supply. This octržištu, gdje su opet veliki energetski subjekti u prednosti. Kako ih podržavaju njihove matične države, a to su uglavnom velike države, male zemlje jednostavno moraju slijediti te procese.

U slučaju popuštanja uzdi regulacije može doći u pitanje i kvaliteta, ali i sigurnost opskrbe. To je na najdrastičniji način došlo do izražaja u Kaliforniji, dakle u najrazvijenijoj saveznoj državi prve ekonomske sile svijeta, SAD-a. Kad se tako nešto moglo dogoditi u najrazvijenijoj državi svijeta, to treba biti znak za poseban oprez u našim daljnjim koracima u reformi našeg elektroenergetskog sektora. Indikativni su i drugi raspadi elektroenergetskih sustava u SAD-u, Engleskoj, Finskoj i Italiji. To znači da se prebrza deregulacija i nekontrolirana liberalizacija, uz nedostatak dugoročne strategije razvitka, vraćaju kao bumerang s teškim i dugoročnim posljedicama. Ovi rizici sigurnosti opskrbe, koji predstavljaju značajan negativan efekat liberalizacije, bili su velika opomena i upozorenje na oprez u liberalizaciji industrije električne energije, što je dovelo do zastoja i usporavanja procesa liberalizacije. Zato se danas sve više pažnje posvećuje sigurnosti opskrbe i zaštiti okoliša, a tek onda liberalizaciji. Liberalizaciju forsiraju oni koji od nje imaju korist.

Nije ostvaren ni cilj izjednjačavanja cijena, jer i dalje egzistira velika razlika u cijenama električne energije među državama i to kako za kućanstva tako i za industriju.

S obzirom na tendenciju zamjene državnih monopola privatnim monopolima i njihovo sve dublje puštanje korijena, može se reći da nema signifikantnog pomaka organizacijske strukture industrije električne energije od monopolske prema konkurencijskoj.

Pozitivni pomaci učinjeni su na podizanju razine kvalitete usluge i povećanju učinkovitosti sektora kroz smanjenu potrebu za izgradnjom i održavanjem rezervnih kapaciteta. Najviše je učinjeno na omogućavanju potrošačkog izbora, jer je većina tržišta potpuno otvorena, što znači da je svim potrošačima omogućen izbor opskrbljivača električnom energijom. To je više formalno pravo, jer većina tržišta još nije dovoljno razvijena, da bi potrošači to pravo mogli efikasno koristiti.

Ovi nalazi istraživanja potvrđuju da glavni ciljevi liberalizacije tržišta električne energije nisu ostvareni, pa se može konstatirati da liberalizacija tržišta električne energije ne ispunjava očekivanja. Naprotiv, prema sadašnjem stanju reformi i prema tendencijama u tim procesima, ti ciljevi, onako kako su na početku reformi zamišljeni i zacrtani, nisu ni ostvarivi.

curred in the most drastic manner in California, i.e. in the most developed state of the first economic power in the world, the United States. When something like this can happen in the most developed state in the world, this should be a sign that particular caution should be exercised in our further steps in the reform of our electrical power sector. Other breakdowns of the electrical power systems in the United States, England, Finland and Italy are also indicative. This means that too rapid deregulation and uncontrolled liberalization, together with the lack of a long-term development strategy, return like boomerangs with grave and long-term consequences. These risks to the security of supply, which represent a significant negative effect of liberalization, were a great admonishment and warning that caution was necessary in the liberalization of the electrical power industry, which led to interruptions and delays in the liberalization process. Therefore, today there is increasing attention devoted to the security of supply and environmental protection, and only then to liberalization. Liberalization is being forced by those who derive benefit from it.

The goal of price uniformity was also not achieved because there continue to exist great differences in the prices of electrical energy among countries, both for households and industry.

Due to the tendency to replace state monopolies with private monopolies, which are increasingly taking deep root, it can be said that there has been no significant shift in the organizational structure of the electrical power industry from monopolistic to competitive.

Positive shifts have been achieved in raising the level of the quality of services and increasing the efficiency of the sector by reducing the need for the construction and maintenance of reserve capacities. The most has been achieved in affording consumers the choice of an electricity supplier, because the majority of the markets are completely open. This is more a formal right because the majority of the markets are not sufficiently developed in order to allow consumers to exercise choice in an effective manner.

These research findings confirm that the primary goals of the liberalization of the electrical power market have not been achieved. Therefore, it can be stated that the liberalization of the electricity markets has not met expectations. On the contrary, according to the current state of reform and the trends in these processes, these goals, as conceived and outlined at the beginning of the reforms, are not feasible.

6 ZAKLJUČAK

Globalizacija, kao svjetski i sveobuhvatni proces, koji mijenja pravila igre u svim sferama rada i života, ima velikog odraza i na elektroenergetskom području. Za elektroenergetske sustave ona znači prvenstveno restrukturiranje, zatim otvaranje elektroenergetskog tržišta i privatizaciju. Iako te globalne procese prate značajni problemi i kontroverze, pa zacrtani ciljevi i konačna rješenja u tim procesima još uvijek nisu postignuti, bez obzira na dvojbe koje se otvaraju, na nova pitanja i probleme na koje se nailazi, navedeni procesi ipak nezaustavlljivo kroče naprijed u najvećem dijelu svijeta. Većina zemalja želi ostvariti opće prihvaćene standarde i oblike organizacije elektroenergetskog sektora i tržišta električne energije, te se uključuje u regionalne i svjetske energetske tokove. Razlike u tim procesima odnose se na varijante organizacije reguliranih i tržišnih djelatnosti i samog tržišta, dinamiku otvaranja tržišta, oblik i sadržaj regulacije i organizaciju i dostupnost javnih usluga.

Razlozi za takvo stanje proizlaze iz činjenice da se radi o vrlo složenim i zahtijevnim procesima, pa u svim zemljama postoje različite vrste problema u svladavanju reformskih zadaća. Na usvojena regulacijska rješenja i planove za prijelazni period, u kojem se uvode nove organizacijske strukture, snažno utječu polazne točke industrije električne energije te političke i institucijske prepreke u svakoj zemlji.

Čini se da deregulacija i liberalizacija, zbog svoje složenosti i netrasiranog puta, a time i značajnog dodatnog troška za elektroenergetski sustav, poništavaju efekte restrukturiranja. To potvrđuju dosadašnji rezultati restrukturiranja elektroenergetskog sektora u svijetu, koji su ispod deklariranih i očekivanih rezultata, a negdje i potpuno suprotni. Obično početna faza restrukturiranja donosi pozitivne ekonomske efekte, koje anuliraju znatni dodatni troškovi regulatora i subjekata tržišne infrastrukture, kao i pretjerana i nekontrolirana glad za maksimalizacijom profita novih privatnih vlasnika, koja je i posebno opasna za sigurnost opskrbe potrošača.

Relativno kratka povijest procesa reforme elektroenergetskog sektora pokazuje da se još dosta toga mora istražiti i naučiti. To najbolje potvrđuju činjenice da sve zemlje koje su krenule u deregulaciju elektroenergetskog sektora vrše stalnu i značajnu reviziju svojih propisa, što se poglavito odnosi na Europsku uniju i njene članice pojedinačno, ali i na ostale zemlje svijeta.

6 CONCLUSION

Globalization, as an all-encompassing worldwide process that changes the rules of the game in all spheres of work and life, has had a great impact on the electrical power area. For electrical power systems, globalization primarily signifies restructuring, followed by the opening of electricity markets and privatization. Although these global processes are accompanied by significant problems and controversies, even if the outlined goals and ultimate solutions have still not been achieved, and despite the doubts they create and the new questions and problems they encounter, these processes are nonetheless forging ahead inexorably in most of the world. The majority of countries want to achieve the generally accepted standards and forms for the organization of the electrical power sectors and electricity markets, and to be included in the regional and world energy trends. The differences in these processes concern variants among the manner of the organization of the regulated and market activities and the markets themselves, the dynamics of market opening, the form and content of regulation and organization, and the accessibility of public services.

Such a situation has occurred because the processes involved are highly complex and demanding. Therefore, all countries have experienced various types of problems in mastering the tasks of reform. The adopted regulatory solutions and plans for the transitional period during which the new organizational structure is to be introduced have greatly depended upon the pre-existing state of the electrical power industry and the specific political and institutional obstacles in each country.

It appears that deregulation and liberalization, due to their complexity, the unchartered path, and significant added expenses for the electrical power system, cancel out the effects of restructuring. This has been confirmed by results to date in the restructuring of the electrical power sectors in the world, which have been below those declared and anticipated, and in some places completely the opposite. Usually, the initial phase of reconstruction brings positive economic effects, which are annulled by the significant added expenses of the regulator and the subjects of the market infrastructure, as well as the excessive and uncontrolled hunger for maximizing profits of the new private owners, which is particularly dangerous to the security of supply to customers.

The relatively brief history of the process of the reform of the electrical power sector shows that there is still a considerable amount that must be investigated and learned. This is best confirmed by the fact that all the countries that have embarked upon the deregulation of the electrical energy sector are constantly and significantly revising their regulations. This particularly applies to the European Union and

Unatoč tome postoji slaganje da se nastavi s:

— uvođenjem konkurencije na veleprodajna i maloprodajna tržišta, dereguliranjem proizvodnje i otvaranjem maloprodaje i
— reguliranjem aktivnosti u mrežnim djelatnostima.

Može se reći da je u današnjoj industriji električne energije učinjen značajan iskorak prema slobodnom tržištu, kao najboljem alokativnom mehanizmu i jamstvu dugoročne efikasnosti, iako još uvijek ima razilaženja u očekivanjima i procjeni daljnjih trendova. Reforme naglašavaju važnost konkurencije i potrošačkog izbora, ali istodobno ne umanjuju činjenicu kako je ekonomija veličine jedan od ključnih pokretača u ovoj industriji. Također, treba imati na umu da deregulacija nije ekvivalent savršene konkurencije, za koju je dobro poznato da je učinkovita. Ili, drugm riječima, provedba deregulacije ne znači i dostizanje savršene konkurencije, što je poseban problem u industriji električne energije zbog njenih specifičnosti. Konkurencijsko tržište ne može kvalitetno funkcionirati, jer nema adekvatne konkurencije na strani ponude. Ponuda često s naporom ili manjkavo zadovoljava potražnju. Uz to nema potrebne mobilnosti električne energije, odnosno prijenosne moći vodova, naročito između pojedinih država i regija.

Tržište je korisno i nužno za postizanje veće ekonomske efikasnosti. Međutim, ono samo po sebi nije u mogućnosti doseći iste rezultate u svim sektorima gospodarstva i upravo zbog toga potreban je nadzor i korekcija tržišta s ciljem minimiziranja njegovih negativnih učinaka. To treba naročito imati u vidu pri konzumaciji tržišta u elektroenergetskom sektoru.

Temeljem svega iznesenog čini se da kreiranje efikasnog tržišta električne energije nije moguće, jer na tom putu stoje mnogobrojne, pa i nepremostive prepreke. To se više odnosi na veleprodajno nego na maloprodajno tržište. Ali to ne znači da treba odustati od liberalizacije, prvenstveno zbog toga što su do sada uloženi veliki napori i resursi u reformu industrije električne energije. Konkurenciju treba poticati u onim djelatnostima industrije električne energije i u onoj mjeri u kojoj ona postiže pozitivne društvene odnosno globalne efekte.

Povećanje globalne efikasnosti poslovanja industrije električne energije biti će to uspješnije, što reforme budu više vođene ekonomskim, a manje špekulativnim razlozima. Čini se da je za povećanje globalne efikasnosti poslovanja u toj industriji od forsirane liberalizacije tržišta puno važnija i korisnija dostupnost novih tehnologija

its member states individually, as well as to the other countries of the world.

Nevertheless, there is agreement to continue with the following:

— the introduction of competition on the wholesale and retail markets through the deregulation of production and the opening of retail, and
— regulation of the activities in network operations.

It can be said that in today's electrical power industry, a significant step has been taken toward a free market, as the best allocative mechanism and guarantee of long-term efficiency, although there are still differences in the expectations and assessments of future trends. Reforms stress the importance of competition and consumer choice, although at the same time without minimizing the fact that the economy of size is one of the crucial movers in this industry. Furthermore, it is necessary to bear in mind that deregulation is not the equivalent of perfect competition, which is well known to be efficient. In other words, the implementation of deregulation does not mean achieving perfect competition, which is a particular problem in the electrical power industry due to its specific characteristics. Market competition cannot function in a quality manner because there is insufficient competition on the supply side. Supply frequently meets demand with difficulty or is insufficient. Moreover, there is inadequate mobility of electrical energy, i.e. the capacities of the transmission lines, especially between individual countries and regions.

A market is useful and necessary for achieving greater economic efficiency. However, in itself it is not able to achieve the same results in all the sectors of the economy. Precisely for this reason, market supervision and correction are necessary with the goal of minimizing the negative effects. This should particularly be borne in mind regarding market consumption in the electrical power sector.

Based upon everything that has been presented, it seems that the creation of an efficient electricity market is not possible because there are numerous and even insurmountable obstacles. This applies more to the wholesale market than the retail market. However, it does not mean that it is necessary to give up on liberalization, primarily because until now great efforts and resources have been invested in the reform of the electrical power industry. Competition should be stimulated in those operations of the electrical power industry and to the extent that achieve positive social or global effects.

Increasing the global efficiency of the operations of the electrical power industry will be more successful if the reforms are implemented more for economic reasons rather than speculative ones. It appears that for increasing the global efficiency of operations in svima, a ne samo velikim energetskim tvrtkama, odnosno razvijenim zemljama.

this industry, the accessibility of new technology to all, not only large energy companies or developed countries, is more important and useful than forced market liberalization.

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RAD FOTONAPONSKOG PARKA NA OTOKU KRETI
A PHOTOVOLTAIC PARK'S PERFORMANCE ON THE ISLAND OF CRETE

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Povoljni klimatski uvjeti otoka Krete i novije zakonodavstvo o obnovljivim izvorima energije pružaju znatan poticaj za uvođenje fotonaponskih elektrana. U ovom prikazu predstavljen je fotonaponski park (FN Park) C. Rokas u Sitiji, Kreta i ocijenjen njegov rad. Taj fotonaponski park, koji je u pogonu od 2002. godine, ima vršnu snagu od 170 kWp. Park se na prikladan način kontrolira godinu dana interno, a izračunavaju se stupanj djelovanja (eng. *performance ratio*) i razni gubici snage (temperaturni, onečišćenje, unutarnji gubici u mreži, energetska elektronika, raspoloživost i međuspoj mreže). Tijekom 2007. park je u mrežu isporučio 230 MWh, i to u rasponu od 335 do 870 kWh dnevno. Proizvodnja na instaliranoj snazi (YF) kretala se od 2 h/d do 5 h/d, a faktor iskorištenja od 58 % do 73 %, što je rezultiralo godišnjim faktorom iskorištenja od 67,36 %.
The favorable climate conditions of the island of Crete and the recent legislation for the utilization of renewable energy sources, provide a substantial incentive for the installation of photovoltaic power plants. In this paper, the grid-connected photovoltaic park (PV park) of C. Rokas SA in Sitia, Crete is presented and its performance is evaluated. The photovoltaic park has a peak power of 170 kWp, and has been in operation since 2002. The park is suitably monitored for a one year internal and the performance ratio and the various power losses (temperature, soiling, internal network, power electronics, grid availability & interconnection) are calculated. The PV Park supplied 230 MWh to the grid during 2007, ranging from 335 kWh to 870 kWh per day. The final yield (YF) ranged from 2 h/d to 5 h/d and the performance ratio (PR) ranged from 58 % to 73 %, giving an annual PR of 67,36 %.

Ključne riječi : faktor angažirane snage, fotonaponski park, gubici snage, ukupna proizvodnja, proizvodnja energije, referentna proizvodnja, faktor iskorištenja, vršna snaga
Key words : capacity factor, energy output, final yield, peak power, performance ratio, photovoltaic park, power losses, reference yield

1 UVOD

Grčko tržište solarne energije naglo raste i privlači ogroman interes investitora zbog nedavno donesenog zakona o sustavu zajamčenih cijena [1] koji jamči cijenu između 0,4 EUR/kWh i 0,5 EUR/kWh za 20-godišnje razdoblje te dopunsku investicijsku subvenciju od 20 % do 40 %. Prema tome, vrijeme povrata investicije u Grčkoj kao zemlji s vrlo visokom insolacijom možda je najniže u cijeloj Europi. Da bi se izvukla korist od takva rasta, analiza stvarnog učinka najvećeg instaliranog fotonaponskog parka (FN park) u Grčkoj, posebice na otoku Kreti s najvišim insolacijskim vrijednostima u Europi, od velike je važnosti za definiranje investicijskih očekivanja u smislu učinkovitosti sustava, a time i gospodarske koristi. Nadalje, ocjena radnog učinka u odnosu na stvarne podatke omogućava otkrivanje pogonskih problema, olakšava usporedbu izvedbeno različitih sustava, te utvrđuje interakciju FN parka s lokalnom mrežom, što je od velikog značaja u nekom velikom autonomnom elektroenergetskom sustavu kao što je kretski [2] i [3].

Pilot projekt FN park C. Rokas lociran je u Ksirolimniju, Sitia na otoku Kreti. U ovom članku analiziran je rad mreže na satnoj, dnevnoj i mjesečnoj osnovi za 2007. godinu. Izvedeni parametri uključuju referentnu proizvodnost, proizvodnost grupe panela, područje krajnjeg prinosa, gubitke pretvorbe primarnog oblika energije, gubitke sustava i stupanj djelovanja.

2 FOTONAPONSKI PARK (FN PARK)

FN park C. Rokas najveći je grčki FN park u pogonu sa instaliranim kapacitetom 170 kWp koji je spojen na 20 kV dalekovod. FN park pokriva ukupno područje od 3 784 m^2 i aktivno područje od 1 142,4 m^2. Fotonaponska elektrana sastoji se od fotonaponskih (FN) modula 1428 MSX 120 Solarex (engl. BP Solar) od polikristalnog silicija. FN moduli su raspoređeni u 120 paralelnih nizova (engl. *strings*), sa po 12 modula u svakom, spojenih na 60 invertera Sunny Boy SB 2500 montiranih na noseću konstrukciju, uz što se nalaze priključne kutije, instrumentacija za mjerenje zračenja i temperature, te sustav za zapisivanje podataka.

Inverteri su priključeni na elektroenergetsku mrežu preko transformatora 0,4/20 kV i brojila električne energije. FN sustav montiran je na noseću konstrukciju od nehrđajućeg čelika okrenutu prema jugu pod kutom od 30°. Taj kut nagiba izabran je da bi se maksimalizirala godišnja proizvodnja energije. Slika 1 prikazuje FN park, a slika 2 prikazuje jednopolnu shemu priključka FN parka na elektroenergetski sustav.

1 INTRODUCTION

The Greek photovoltaic market is rapidly growing, attracting an enormous investment interest due to the recently launched feed-in tariff (RES law) [1] guarantying a price between 0,4 EUR/kWh and 0,5 EUR/kWh for a 20-year period and a supplementary investment subsidy at 20 % to 40 %. Therefore, the payback time of an investment in Greece with very high insolation may be the lowest in whole Europe. To benefit from this growth, the actual performance analysis of the largest installed photovoltaic Park (PV park) in Greece, and especially on the island of Crete with one of the highest insolation values across Europe, is of great importance in order to set the investor's expectations for system performance and the associated economic return. Furthermore, the performance evaluation with real data can allow the detection of operational problems, facilitate the comparison of systems that may differ with respect to design, and evaluate the interaction of the Park with the local grid, which is of high significance in a large autonomous electric system, such the Cretan one [2] and [3].

The pilot PV Park C. Rokas is located in Xirolimni, Sitia, Crete. In this paper, the performance of the grid connected for the year 2007 has been analysed on hourly, daily and monthly bases. The derived parameters include reference yield, array yield, final yield array, capture losses, system losses, and performance ratio.

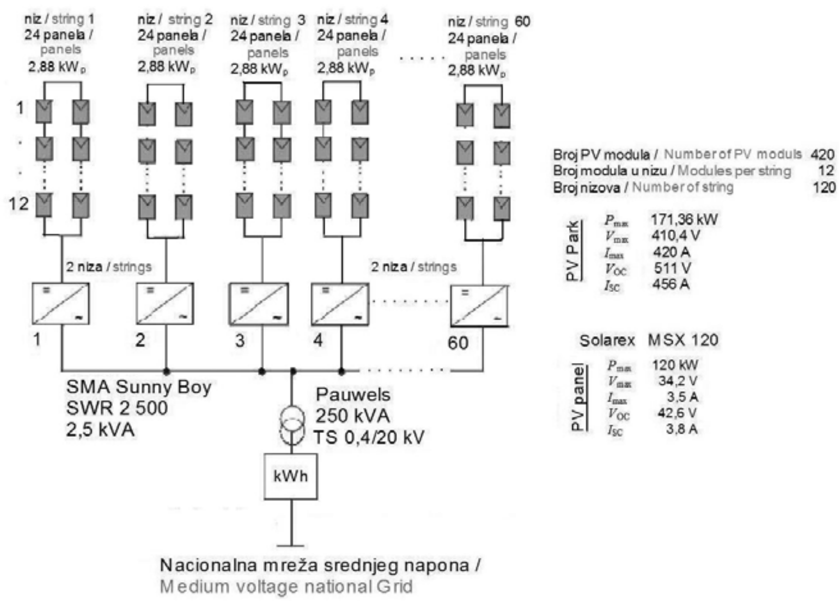
2 PHOTOVOLTAIC PARK

The PV Park is the largest operating PV Park in Greece with an installed capacity of 170 kWp grid connected to a 20 kV TEP transmission line and covering a total surface area of 3 784 m^2, and an active area of 1 142,4 m^2. The park is comprised of a 1 428 MSX 120 Solarex (BP Solar) polycrystalline silicon PV modules. The PV modules are arranged in 120 parallel strings, with 12 modules in each, and connected to sixty Sunny Boy SB 2500 inverters installed on the supporting structure, plus connection boxes, irradiance and temperature measurement instrumentation, and data logging system.

The inverters are linked to the national grid via a 0,4/20 kV transformer and an electrical energy meter. The PV system is mounted on a stainless steel support structure facing south and tilted at 30°. Such a tilt angle was chosen to maximise yearly energy production. Figure 1 shows the PV park, and Figure 2 shows a schematic block circuit diagram of the system's electrical connection.

Slika 1 — Pogled na FN park C. Rokas SA — FN moduli nagnuti su 30°, orijentirani prema jugu (u pozadini susjedna vjetroelektrana)

Figure 1 — View of the C. Rokas SA Photovoltaic Park, the FN modules are tilted at 30° and oriented south (the adjacent wind park in the background)



Slika 2 — Shematski blok dijagram FN sustava

Figure 2 — Schematic block circuit diagram of the FN system

3 ANALIZA SUSTAVA

FN sustav parka detaljno je analiziran kako bi se procijenila učinkovitost sustava pri radu paraleno s lokalnom elektroenergetskom mrežom. Za ocjenu učinkovitosti FN parka proračunati su ukupna proizvodnost (Y_F), referentna proizvodnost (Y_R), stupanj djelovanja - performance ratio (PR) i faktor opterećenja (CF) prema definiciji standarda IEC 61 724 [4].

Ukupna proizvodnost (Y_F) definira se kao godišnja,

3 SYSTEM ANALYSIS

The PV Park system has been fully monitored to assess its performance with the local power grid. To evaluate the PV Park performance, the final yield (Y_F), the reference yield (Y_R), the performance ratio (PR) and the capacity factor (CF) were calculated as defined by the IEC Standard 61 724 [4].

The final yield (Y_F) is defined as the annual, monthly or daily net AC (alternating current) energy output (E) of the system divided by the peak power (P_r) of mjesečna ili dnevna neto proizvodnja električne energije na srednjenaponskoj strani priključnog transformatora (E) podijeljena s vršnom snagom (P_r) instaliranog fotonaponskog sustava u standardnim ispitnim uvjetima (SIU) sunčeva zračenja od 1 000 W/m^2 i temperature ćelija od 25 °C:

the installed PV array at Standard Test Conditions (STC) of 1 000 W/m^2 solar irradiance and 25 °C cell temperature:

$$Y_F = \frac{E}{P_r} . \tag{1}$$

Referentna proizvodnost (Y_R) je ukupna solarna insolacija na plohi H_t (kWh/m^2) podijeljena s referentnim zračenjem za grupu FN panela (kW/m^2); dakle, referentna proizvodnost je broj vršnih sunčanih sati:

The reference yield (Y_R) is the total in-plane solar insolation H_t (kWh/m^2) divided by the array reference irradiance (kW/m^2); therefore, the reference yield is the number of peak sun-hours:

$$Y_R = \frac{H_t}{1} \frac{\left[\text{kWh/m}^2\right]}{\left[\text{kW/m}^2\right]} = \frac{H_t}{1} \left[\text{h}\right] . \tag{2}$$

Stupanj djelovanja (PR) je ukupna proizvodnost podijeljena s referentnom proizvodnosti; on predstavlja ukupne gubitke u sustavu s pretvaranjem istosmjerne struje (DC) u izmjeničnu (AC). Tipični gubici FN parka uključuju gubitke zbog degradacije panela (η_{deg}), temperature (η_{tem}), onečišćenja (η_{soil}), unutarnje mreže (η_{net}), invertera (η_{inv}), transformatora (η_{tr}) i raspoloživosti sustava te priključenja na mrežu (η_{ppc}). Stoga se stupanj djelovanja (PR) može izraziti kao:

The performance ratio is the final yield divided by the reference yield; it represents the total losses in the system when converting from nameplate DC (direct current) rating to AC output. The typical losses of a PV park include losses due to panel degradation (η_{deg}), temperature (η_{tem}), soiling (η_{soil}), internal network (η_{net}), inverter (η_{inv}), transformer (η_{tr}) and system availability and grid connection network (η_{ppc}). Therefore, the PR can be expressed as:

$$PR = \frac{Y_F}{Y_R} = \eta_{deg} \cdot \eta_{tem} \cdot \eta_{soil} \cdot \eta_{net} \cdot \eta_{inv} \cdot \eta_{tr} \cdot \eta_{ppc} . \tag{3}$$

Proizvodnost grupe panela (Y_A) definira se kao godišnja ili dnevna proizvodnja energije FN područja podijeljena s vršnom snagom (P_R) instalirane grupe FN panela; gubici sustava (L_S) uključuju gubitke konverzije invertera i transformatora, a gubici prihvata energije unutar grupe panela (L_C) uzrokovani su gubicima unutar FN modula u toj grupi:

The array yield (Y_A) is defined as the annual or daily energy output of the PV array divided by peak power of the installed PV, the system losses (L_S) are gained from inverter and transformer conversion losses, whereas the array capture losses (L_C) are due to PV array losses:

$$Y_A = \frac{E_A}{P_R} , \tag{4}$$

$$L_C = Y_R - Y_F , \tag{5}$$

$$L_S = Y_A - Y_F . \tag{6}$$

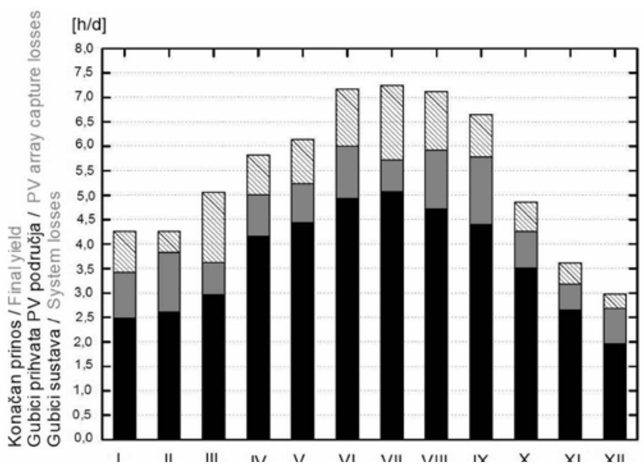
Konačno, faktor opterećenja (CF) definira se kao omjer stvarne godišnje proizvodnje električne energije i električne energije koju bi FN park proizveo kada bi radio snagom punog kapaciteta (P_r) neprestano cijele godine:

Finally, the capacity factor (CF) is defined as the ratio of the actual annual energy output and the amount of energy the PV Park would generate if operating at full rated power (P_r) for 24 hours per day for a year:

$$CF = \frac{Y_F}{8\ 760} = \frac{E}{P_{r*}8\ 760} = \frac{H_t}{P_{r*}8\ 760} \quad . \qquad (7)$$

Trenutno globalno zračenje u zoni grupe FN modula, temperatura okoline, izlazna DC snaga grupe FN modula i izlazna AC snaga FN parka bili su mjereni svakih 10 minuta i spremani u bazu podataka. Mjesečna proizvodnja električne energije na priključnoj točki mreže također je bila dana od grčke elektroprivrede PPC (odnosno operatora mreže). Potpuni pogonski podaci iz baze podataka za 2007. godinu bili su uprosječeni svakih 10 minuta tijekom tipičnog dana i to za cijeli mjesec. Slika 3 prikazuje ukupnu mjesečnu uprosječenu insolaciju u zoni zajedno s mjesečnom temperaturom okoline uprosječenom kroz sate preko dana.

The incident global irradiance in array plane, the ambient temperature, the DC array output power, and the PV Park AC output power were measured every 10 minutes and stored in the logger system. The monthly AC output energy at the grid connection point was also given by the Greek PPC (grid connection network). Complete operation data from the logger for the year 2007 was averaged for every 10 minutes during a typical day per month. Figure 3 shows the monthly averaged total in-plane insolation together with the monthly ambient temperature averaged over the daytime hours.



Slika 3 — Ukupna mjesečna uprosječena insolacija u zoni i temperatura okoline uprosječena kroz sate preko dana u godini 2007.

Figure 3 — Monthly averaged total in-plane insolation and ambient temperature averaged during the daytime hours over the year 2007

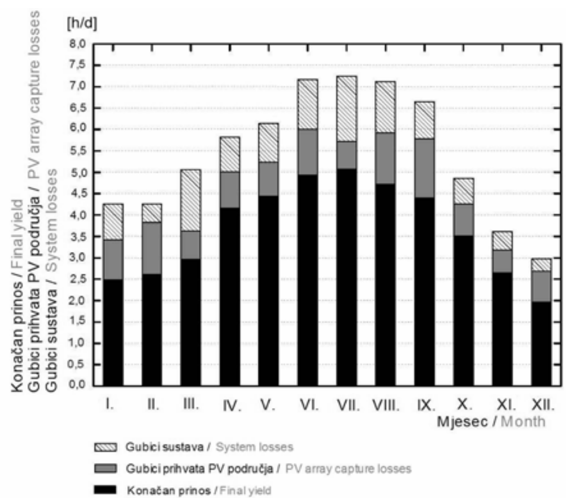
Najviša vrijednost ukupne insolacije u plohi iznosila je u srpnju 225 kWh/m^2, a najniža u prosincu 92 kWh/m^2. Godišnja insolacija iznosila je 1985 kWh/m^2 a srednja temperatura okoline 16,46 °C. U 2007. godini FN park proizveo je 229 MWh, u rasponu od 10,4 MWh (prosinac) do 27 MWh (srpanj) mjesečno. Slika 4 prikazuje mjesečno uprosječeni dnevni konačni prinos, područne gubitke prihvata i gubitke sustava. Mjesečno uprosječena dnevna prozvodnost grupe panela kretala se od 2,25 h/d (prosinac) do 6,6 h/d (srpanj), a ukupna proizvodnost od 1,95 h/d do 5,07 h/d. Prosječna godišnja

The highest value of total in-plane insolation was in July with 225 kWh/m^2, and the lowest in December with 92 kWh/m^2. The annual insolation was 1 985 kWh/m^2 and the mean ambient temperature was 16,46 °C. The PV Park generated 229 MWh in 2007, ranging from 10,4 (December) to 27 MWh (July). Figure 4 shows the monthly averaged daily final yield, array capture losses and system losses. The monthly averaged daily array yield ranged from 2,25 (December) to 6.6 h/d (July), and the final yield from 1,95 h/d to 5,07 h/d. The average annual final yield and reference yield was 1 337 ukupna proizvodnost i referentna proizvodnost iznosili su 1 337 sati odnosno 1 984 sati. Mjesečno uprosječeni dnevni gubici grupe FN modula kretali su se od 0,54 h/d (studeni) do 1,38 h/d (rujan), a gubici sustava od 0,29 h/d (prosinac) do 1,52 h/d (srpanj). Stupanj djelovanja bio je raspoređen u rasponu od 58 % do 73 %, dok je godišnja srednja vrijednost bila 67,36 %.

Ukupna godišnja proizvodnost od 1.337 kWh/kWp za FN park značajno je viša od FN parkova u Njemačkoj [5] i slična je FN parkovima u južnoj Španjolskoj [6], što ilustrira ogromne potencijale ulaganja u otok Kretu. Prosječni godišnji faktor angažirane snage iznosio je 15,26 %.

and 1 984 hours, respectively. The monthly average daily array losses ranged from 0,54 h/d (November) to 1,38 h/d (September), and the system losses from 0,29 h/d (December) to 1,52 h/d (July). The performance ratio was distributed within the range of 58 % to 73 %, and the annual mean value was 67,36 %.

The annual final yield of 1 337 kWh/kWp for the PV Park is significantly higher than PV parks operated in Germany [5] and similar to parks operated in Southern Spain [6], demonstrating the huge potential of an investment in the island of Crete. The average annual capacity factor was 15,26 %.



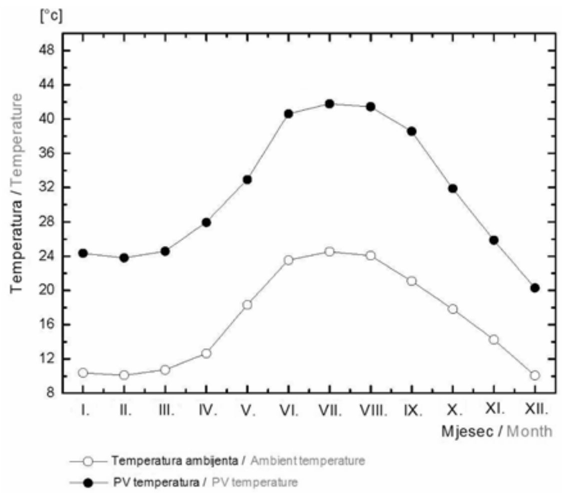
Slika 4 — Mjesečno uprosječeni dnevni konačni prinos, gubici prihvata FN područja i gubici sustava
Figure 4 — Monthly averaged daily final yield, FN array capture losses and system losses

Metodologija koja se koristi za analitički proračun raznih gubitaka FN parka može se opisati kako slijedi: Sučevo zračenje u plohi, temperatura okoline preko dana, DC snaga grupe FN modula i izlazna AC snaga parka uprosječene su u 10-minutnim intervalima tijekom tipičnog dana mjesečno. Nominalna trenutna DC snaga grupe FN modula (10 minutni prosjek) i ukupna godišnja izlazna energija izračunavaju se uporabom podataka o sunčevu zračenju i tehničkih specifikacija korištenih fotonaponskih panela. Zatim se stvarna izlazna snaga grupe FN modula postepeno simulira uračunavanjem različitih gubitaka uslijed; degradacije FN modula, gubitaka uzrokovanih temperaturom i onečišćenjem. Isti se put slijedi za izračun gubitaka međuspoja, invertera i transformatora koreliranjem stvarne proizvodnje grupe FN panela s proizvodnjom energije FN parka na bazi 10-minutnih podataka. Ova metoda pruža realnu procjenu, budući da su razni gubici stavljeni u međusobnu vezu i izravno povezani sa stvarnom trenutnom proizvodnjom energije FN panela i FN parka.

The methodology followed to analytically calculate the various losses of the PV Park can be described as follows: The in-plane solar radiation, the ambient daytime temperature, the array DC power and the park AC output power are averaged with a 10 minutes frequency during a typical day per month. The nominal instantaneous array DC power per 10 minutes and the total array annual output energy are calculated using the solar radiation data and the technical specifications of the photovoltaic panels used. Then, the real array output power is simulated gradually adding various losses of the array; the degradation modulus, the temperature and the soiling losses. The same routine is followed for the calculation of the interconnection, inverter and transformer losses by correlating the real array power output with the PV Park power output with a 10 minutes frequency. This method gives a realistic estimate, since the various losses are interrelated and directly linked with the instantaneous real power output of the PV panels and the PV Park.

Učinkovitost jednog FN panela ovisi o radnoj temperaturi i energijskoj gustoći sunčeva zračenja. Kako se povećava temperatura FN panela, učinkovitost se linearno smanjuje, budući da se vršna snaga FN panela odnosi na SIU uvjete. U različitim temperaturama izlazna snaga FN panela ovisi o razlici temperature panela i SIU temperature (T_C – T_{STC}) te o energijskoj gustoći (G) vjerojatnog sunčeva zračenja. Na slici 5 prikazani su radna temperatura FN modula i temperatura okolne mjerene u satima između izlaska i zalaska Sunca kroz promatrano razdoblje.

The efficiency of a PV panel depends on the operation temperature and the power density of the solar radiation. As the temperature of the PV panels increases, the efficiency decreases linearly, since the peak power of the PV panels refers to STC conditions. In different temperatures, the output power of the PV panels depends on the difference between the panel temperature and the STC temperature (T_C – T_{STC}) and on the power density (G) of the incident solar radiation. The PV module monthly operating temperature and the ambient temperature measured during daylight hours over the monitored period are shown in Figure 5.



Slika 5 — Mjesečno prosječna satna temperatura zraka okoline i temperatura FN modula mjerena u satima od izlaska do zalaska Suncaza 2007.

Figure 5 — Monthly average hourly ambient air and FN module temperature measured during daylight hours for 2007

Ljeti je mjesečno prosječna satna temperatura FN modula varirala između 22 °C i 31 °C, dok se ambijentalna temperatura kretala između 13 °C i 18 °C. Zimi je prosječna satna temperatura FN modula varirala između 10 °C i 12 °C, dok se ambijentalna temperatura kretala između 6 °C i 8 °C.

Koeficijent temperaturnih gubitaka (η_{tem}) može se izračunati kao:

In summer, the monthly average hourly PV module temperature varied within 22 °C do 31 °C, and the ambient temperature ranged between 13 °C and 18° C. In winter, the average hourly PV module temperature varied from 10 °C to 12 °C, and the ambient temperature ranged between 6 °C and 8 °C.

The temperature losses coefficient (η_{tem}) can be calculated as:

$$n_{tem} = 1 + \beta \left(T_c - 25\right), \quad (8)$$

gdje je:

β – temperaturni faktor FN panela,
T_C – temperatura solarne ćelije,
T_A – temperatura zraka

where;

β – the temperature factor of the PV panel,
T_C – PV cell temperature,
T_A – the air temperature,

Temperatura solarne ćelije (T_C) u korelaciji je s temperaturom zraka (T_A) kako slijedi:

The PV cell temperature (T_C) is correlated with the air temperature (T_A) as follows:

$$T_c = T_a + \frac{G}{G_{NOCT}}(T_{NOCT} - 20) = T_a + \frac{G}{800}(T_{NOCT} - 20) \qquad (9)$$

gdje je:

T_{NOCT} – nominalna radna temperatura ćelije i
G – energetska gustoća u određeno vrijeme,
G_{NOCT} – energetska gustoća pri nominalnoj radnoj temperaturi ćelije

Koeficijenti temperaturnih gubitaka izračunati su na temelju 10-minutnih podatala i godišnji gubici zbrojeni su na 7,12 %.

U uvjetima neprekidnog rada FN paneli naposljetku postanu pokriveni tankim slojem prljavštine i prašine, čime se smanjuje količina svjetla što dospijeva do svake ćelije. Količina gubitka snage zbog takva onečišćenja (η_{soil}) ovisi o vrsti prašine (lokalne poljoprivredne djelatnosti), dužini vremena proteklog od zadnje kiše i o programu čišćenja i održavanja. Za konkretni FN park, mjesečni koeficijenti empirički su procijenjeni na temelju studije PVUSA [7] i podataka o padalinama na licu mjesta. Gubici od onečišćenja iznosili su 4 % do 5 % u zimskom i 6 % do 7 % u ljetnom razdoblju, što je rezultiralo godišnjim gubicima od 5,86 %.

Kad su se temperaturni gubici i gubici od onečišćenja dodali nominalnoj proizvodnji energije bez gubitka:

where:

T_{NOCT} – the nominal temperature operational cell temperature and
G – the power density at the particular time,
G_{NOCT} – the power density at the nominal temperature operational cell temperature

The temperature losses coefficients were calculated with a 10 minutes frequency and the annual losses were summed to 7,12 %.

The PV panels under continuous operation eventually become covered with a fine layer of dirt and dust, decreasing the amount of light reaching each cell. The amount of power loss due to soiling (η_{soil}) depends on the type of dust (local agricultural activities), the length of time since the last rainfall and the cleaning maintenance schedule. For the specific PV Park, the monthly coefficients were empirically estimated based on the PVUSA study [7] and the rainfall data of the site. The soiling losses were 4 % to 5 % during the winter and 6 % to 7 % during the summer period, resulting in annual losses at 5,86 %.

By adding the temperature and soiling losses to the nominal array power output without losses:

$$P_{PV} = \frac{P_r \cdot G}{1} \;, \qquad (10)$$

primijećeno je neslaganje od 5 % u usporedbi sa stvarnom zabilježenom izlaznom snagom. To se neslaganje može pripisati gubicima od degradacije FN panela (η_{deg}) tijekom starenja, budući da je FN park u punom pogonu od 2002. godine. To se u potpunosti slaže s eksperimentalnim studijama kao i s izjavama i jamstvima proizvođača, time što prve energetske deklaracije navode 5 % uz maksimalni vijek trajanja od 20 % [8].

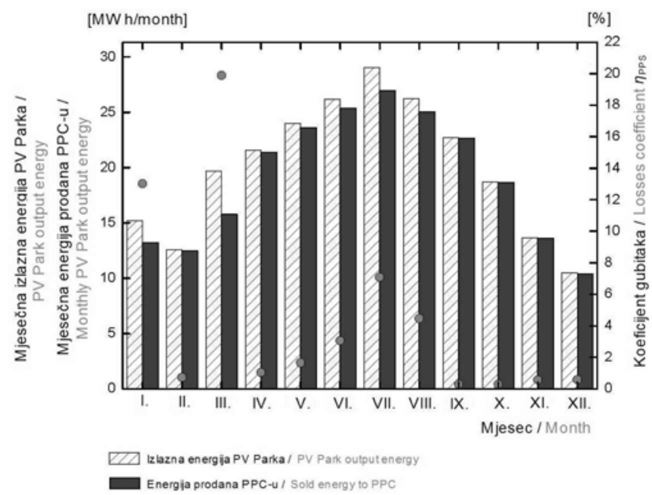
Gubici pretvorbe invertera [pretvaranje istosmjerne struje (DC) u izmjeničnu struju (AC)] određeni su na temelju 10-minutnih podataka oduzimanjem izlazne DC snage grupe FN panela od izlazne AC snage te normaliziranjem gubitaka od DC ožičenja i međuspoja (η_{net} = 6 %) i gubitka transformatora (η_{tr} = 2 %).

a 5 % mismatch compared with the real recorded output power was observed. This mismatch can be attributed to the PV panel degradation losses (η_{deg}) during ageing, as the PV Park has been in full operation since 2002. This is in full agreement with experimental studies and manufacturers declarations and warranties, whereas the initial power declarations lie at 5 % with a lifetime maximum of 20 % [8].

The inverter [direct current (DC) to the alternating current (AC)] conversion losses were calculated with a 10 minutes frequency by subtracting the array DC output power from the AC output power, and by normalizing the DC wiring & interconnection losses (η_{net} = 6 %), and the transformer losses (η_{tr} = 2 %).

Prema tome, izračunati gubici invertera (η_{inv}) zbrojeni su na 7,84 %. Konačno, gubici od mjesečne raspoloživosti i priključivanja nacionalne mreže (η_{ppc}) izračunati su kao omjer prodane energije PPC-u podijeljene ukupnom izlaznom AC energijom parka, kako je prikazano na slici 6.

Therefore, the calculated inverter losses (η_{inv}) are summed to 7,84 %. Finally, the monthly availability and national grid connections losses (η_{ppc}) were calculated as the ratio of energy sold to the PPC divided by the AC overall output energy of the park, and are shown in Figure 6.



Slika 6 — Mjesečna izlazna energija FN parka, mjesečna energija prodana PPC-u, i koeficijent gubitaka od raspoloživosti i priključivanja nacionalne mreže (η_{PPC})

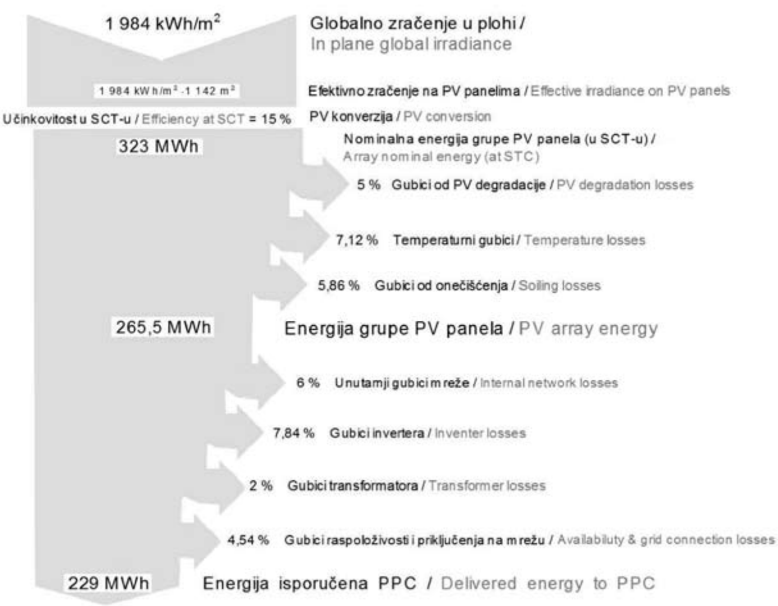
Figure 6 — Monthly FN Park output energy, monthly sold energy to PPC, and availability and national grid connections losses coefficient (η_{PPC})

Gubici od neraspoloživosti mreže i priključka (η_{PPC}) kreću se od 0,3 % (listopad i studeni) do 19,9 % (ožujak), uz godišnji prosjek od 4,54 %. Gubici su vrlo niski (<1 %) u veljači, travnju, rujnu, listopadu i prosincu, rastu od svibnja do srpnja, dok su za siječanj i ožujak krajnje visoki. Za sada se ti podaci ne mogu objasniti, jer nema podataka za razdoblja mirovanja mreže. Međutim, može se pretpostaviti da u siječnju i ožujku ima značajno razdoblje kada mreža odbacuje energiju iz parka. Ovo je značajna karakteristika ako se uzme u obzir da je autonomni elektroenergetski sustav Krete najveći sustav u Grčkoj s najvišom nacionalnom stopom rasta potražnje za elektroenergijom [2].

Razni godišnji gubici FN parka mogu se sabrati u Sankeyevu dijagramu na slici 7.

The availability and grid connection losses (η_{PPC}) range from 0,3 % (October and November) to 19,9 % (March), with an annual average of 4,54 %. The losses are very low (<1 %) in February, April, September, October and December, there is an increase from May until July, whereas for January and March the losses are extremely high. The data cannot be explained at present, since there are no available data for the grid off periods. Nevertheless, it can be postulated that in January and March, there is a significant period, where the grid rejects the power input from the park. This is an important feature, taking into account that Crete's autonomous electrical system is the largest one in Greece with the highest rate of increase nationwide in energy and power demand [2].

The various annual losses of the PV Park can be summarized in the Sankey diagram of Figure 7.



Slika 7 — Sankeyev dijagram proračunatih gubitaka u FN parku; parametri u podebljanom fontu izvedeni su iz stvarnih mjerenja u okviru analize neobrađenih podataka

Figure 7 — Sankey diagram of estimated losses in the FN Park, the parameters in bold are derived from the real measurements raw data analysis

4 ZAKLJUČCI

Prezentirano je prvo dugoročno praćenje i analiza rada jednog FN sustava priključenog na mrežu na otoku Kreti. Moguće je donijeti sljedeće zaključke:

- prosječna godišnja proizvodnja energije FN parka u 2007. godini iznosi 1 337 kWh/kWp,
- prosječni godišnji stupanj djelovanja parka iznosi 67,36 %,
- prosječni godišnji faktor angažirane snage iznosi 15,26 %.

Zaključci u ovom prikazu, u svjetlu nedavno najavljenog plana instaliranja fotonaponskog parka snage 50 MW u megalopolisu Grčke, od velikog su značaja.

4 CONCLUSIONS

The first long term monitoring and performance analysis of a grid connected PV system in the island of Crete has been investigated. The following conclusions can be drawn:

- average annual PV Park energy output in 2007 is 1 337 kWh/kWp,
- average annual performance ratio of the park is 67,36 %,
- the average annual capacity factor is 15,26 %.

The conclusions herein, in view of the recently announced plan to install a 50 MW photovoltaic park in Megalopolis Greece, are of great importance.

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PROCJENA RIZIKA STRADAVANJA RADNIKA DISTRIBUCIJE

ASSESSMENT OF RISK TO DISTRIBUTION WORKERS

Pavle Filko, Osijek, Hrvatska

Ovaj rad predstavlja analizu rizika stradavanja radnika na održavanju postrojenja srednjeg napona distribucijske tvrtke. Proizašao je iz niza istraživanja (povrede na radu, vrijeme na održavanju postrojenja, kvarovi sa zemljom i kvarovi uzemljivača) i predstavlja skup svih prikupljenih relevantnih informacija o ugrozi radnika.

Važnost ovoga rada je što se u osnovi bavi kvarovima, zastojima, prekidima, ali i popravcima (predviđanjem, otkrivanjem i otklanjanjem kvarova), održavanjima, obnavljanjima, unaprjeđenjima i poboljšanjima tehničkih sustava, kao i posljedicama kvarova, kako u tehničkim sustavima, tako i u okolišu tehničkih sustava.

Radnici distribucije električne energije najvećim su dijelom svog radnog vremena na poslovima održavanja elektroenergetskih objekata, tj. električnih mreža i postrojenja srednjeg i niskog napona. Tijekom rada nalaze se u potencijalno opasnoj okolini koja može ugroziti njihovo zdravlje i život. Naravno da moraju biti obučeni za rad na siguran način i koristiti sredstva zaštite na radu, no opasnosti se time ne uklanjaju u potpunosti, nego se tek time smanjuje mogućnost ozljede i njezina veličina. Sve tvrtke, pa i one koje se bave distribucijom električne energije, vode računa o troškovima u kojima veliki dio otpada na troškove ljudskog rada. Trošak je stoga i ozljeda radnika za vrijeme rada, što zbog bolovanja, što zbog mogućih odšteta koje će sve više biti značajan faktor u poslovanju tvrtke. Stoga je potrebno unaprijed sagledati sve potencijalne opasnosti koje mogu ugroziti zdravlje i život radnika za vrijeme rada na održavanju. Upravljanje takvim rizicima postat će sve više zadaća svih tvrtki, ne toliko iz humanih razloga, koliko iz razloga držanja troškova pod kontrolom.

This article presents an analysis of the risk to workers maintaining the medium-voltage facilities of distribution companies, as derived from a series of investigations (injuries at work, time spent on equipment maintenance, ground faults and failures in the grounding system) and represents a group of all the relevant information collected on hazards to workers.

The importance of this study is that it is basically concerned with failures, stoppages and interruptions but also repairs (the forecasting, detecting and eliminating of failures), maintenance, replacement, advancements and improvements in the technical systems, as well as the consequences of failures in technical systems and the surroundings thereof. Electricity distribution workers spend most of their working time on the tasks of maintaining electric power facilities, i.e. electricity networks and medium-voltage and low-voltage electric power facilities. While they are working, they are in a potentially hazardous environment that can endanger their health and lives. Naturally, they must be trained to work in a safe manner and use protective equipment. This does not completely eliminate the hazards but in this way the potential for injury and the severity thereof are reduced. All companies, including those engaged in the distribution of electrical energy, take costs into account, much of which are for human labor. Worker injury during working time is also an expenditure, due to sick leave and potential damages, which will be increasingly significant factors in company operations. Therefore, it is important to review all the potential hazards that can endanger the health and life of a worker during maintenance work. The management of such risks will become a growing task for all companies, less for humane reasons than for keeping costs under control.

Ključne riječi: gradska trafostanica 10(20)/0,4 kV, kvar, mreža i postrojenje srednjeg napona, pokazatelj pouzdanosti, povrede na radu, rizik, sustav uzemljenja, vrijeme održavanja

Key words: failure, grounding system, injury at work, maintenance time, medium-voltage network and facilities, 10(20)/0,4 kV municipal substation, reliability index, risk

1 UVOD

Ljudska priroda potiče na uporabu svega vrjednijeg radi ostvarenja povećanja vrijednosti. Tako su u posljednje vrijeme i tehnički sustavi prijenosa i distribucije električne energije pojačano izlagani riziku kako bi svojim radom donosili povećanje vrijednosti svom vlasniku.

Prodaja električne energije kupcima, u Hrvatskoj, ovisi (još više u neposrednoj budućnosti) i o kvaliteti kao i o količini isporučene električne energije, a to pak ovisi o mjestu, broju i dužini trajanja kvarova opreme. Mjesto i broj kvarova opreme ovise o veličini potrošnje, o stanju opreme kao i o njenom održavanju. O stanju opreme također ovisi i rizik stradavanja radnika koji je održavaju. No, istodobno ti radnici na održavanju svojim radom povećavaju njezinu kvalitetu, što smanjuje broj kvarova i broj mjesta kvara te to traži povećanje njihovog angažmana. Veći radovi na održavanju znače i veći rizik od stradavanja radnika. Stoga se postavljaju pitanja: koliko često moraju ekipe odlaziti u postrojenja zbog održavanja, koji je rizik od nesreća na radu od udara električne energije za radnike distribucije, kako smanjiti te rizike?

2 OSNOVNE POSTAVKE TEORIJE RIZIKA

2.1 Pretpostavke

- postrojenja nemaju stalnu posadu pa su za preventivno, korektivno i kombinirano održavanje potrebne planirane posjete ekipa radnika i njihove radne aktivnosti u potencijalno opasnom okolišu,
- postrojenje bi zbog lošijeg održavanja bilo sklonije kvarovima, nerentabilnije, ali i opasnije za radne ekipe,
- postoji i stanje održavanja kada bi prečesto i preveliko održavanje značilo veliki trošak za rad ekipa, a raspoloživost postrojenja (kvaliteta postrojenja) se ne bi toliko bitno dodatno povećala,
- u postrojenju se može dogoditi potencijalno opasno stanje za radnike na održavanju kada se za vrijeme njihovog boravka (događaj A) dogodi kvar u mreži ili ovom ili susjednom postrojenju 10 kV (događaj B) s velikom strujom kvara kroz uzemljivač. To stanje može biti još opasnije, ako u postrojenju u tim trenucima postoji i makar djelomični kvar uzemljivača (događaj C).

Jedan od prioritetnih rizika je stradavanje radnika u pogonu. Za svaki prioritetni rizik

1 INTRODUCTION

It is in human nature to utilize everything of value in order to create increased value. Thus, in recent times there has been increased risk exposure in technical systems for the transmission and distribution of electricity in order for operations to yield increased value to their owners.

The sale of electricity to customers in Croatia also depends (and will depend even more so in the immediate future) on the quality as well as the quantity of electricity supplied, and thus upon the location, number and duration of equipment failures. The location and number of equipment failures depend upon consumption, the condition of the equipment and its maintenance. The risk of harm to the workers who maintain the equipment also depends upon its condition. However, at the same time these maintenance workers are increasing the quality of the equipment, thereby reducing the number of failures and the number of failure sites, which requires increased engagement on the workers' part. Increased maintenance work also means greater risk of harm to workers. Therefore, the following questions are posed: how often must teams go out to the equipment for maintenance, what are the risks of work-related accidents from electrical shocks to distribution workers and how can these risks be reduced?

2 THE BASIC THESIS OF RISK THEORY

2.1 Assumptions

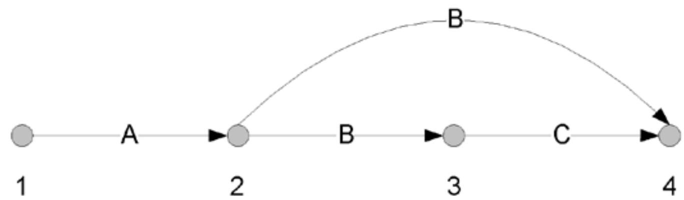
- Facilities do not have permanent crews. Therefore, for preventive, corrective or combined maintenance it is necessary to call in a team of workers and organize their working activities in a potentially hazardous environment.
- Poor maintenance would make facilities would be more susceptible to failures, unprofitable but also hazardous for working teams.
- There is also a state of maintenance when overly frequent and excessive maintenance would signify a significantly large expense for the services of the team, and the availability of the facility (quality of the facility) would not be significantly increased.
- In a facility, a potentially hazardous state for maintenance workers can occur when (Event A) a failure occurs while they are present in the network of either this or a neighboring facility of 10 kV (Event B), with high fault current flowing through the grounding electrode. This state can be even more dangerous if at these moments there is even a partial failure of the grounding system of the facility (Event C).

utvrđuje se njegov rizični lanac i daje pripadni model osnovnog uzroka, neposrednih uzroka, incidenata, akcidenta, neposrednih posljedica i zakašnjelih posljedica:

— osnovni uzrok: pojava napona na uzemljenim metalnim masama (B) ili/i s djelomičnim kvarom uzemljivača (B+C),
— neposredni uzrok: boravak radnika u postrojenju (A),
— incident: potencijalno opasni događaj za radnike u postrojenju, trenutak kvara, B, B+C,
— akcident: događaj strujno-naponskog udara kojem je ili su izloženi radnik/ci za vrijeme izvođenja radova na održavanju elektroenergetskog postrojenja,
— neposredne posljedice: ozljeda, odnosno smrt radnika zbog utjecaja strujno-naponskog udara na tijelo,
— zakašnjele posljedice: ozljeda, smrt, patogene promjene u porodici i društvu, materijalne štete.

One of the priority risks is harm to a worker during operation. For each priority risk, the risk chain is determined and the corresponding model of the basic cause, indirect causes, incidents, accidents, direct consequences and delayed consequences is provided:

— basic cause: voltage occurring on grounded metallic masses (B) and/or partial failure of the grounding system (B+C),
— indirect cause: presence of the worker in the facility (A),
— incident: potentially dangerous event to workers in the facility, moment of failure, B, B+C,
— accident: electrical shock event to which the workers are exposed while performing maintenance work on an electric power facility,
— indirect consequences: the injury or death of a worker due to the effect of an electrical shock event on the body,
— delayed consequences: injury, death, pathogenic changes in the family and society, pecuniary damages.



Slika 6 — Model rizika
Figure 6 — Risk model

Komponenta:

— A — prisutnost radnika u postrojenju (samo u radno vrijeme, tj. od 7 do 15 sati),
— B — kvar u distribucijskoj mreži (10 kV, svi kvarovi sa zemljom),
— C — kvar uzemljivača koji taj rizik čini još opasnijim.

Components:

— A — presence of workers in the facility (only during working hours, i.e. from 7 a.m. to 3 p.m.),
— B — failure in the distribution network (10 kV, all ground faults),
— C — fault in the grounding system, increasing the hazard of this risk.

2.2 Osnovne postavke

— sustav je cjelina koja stvara izlaze Y za dane ulaze X,
— sastoji se od podsustava (oprema, operatori) koji su povezani slijedno (serijski) ili sprežno (paralelno) koji su također sustavi,
— sustav radi pod upravom i nadzorom čovjeka, jednog ili više njih. Nazivamo ih rukovodni posrednici ili agenti,
— svaki agent koristi resurse sustava R (oprema, radnici) u okolišu sustava E, tako da sustav generira izlaz Y u jedinici vremena iz

2.2 Basic assumptions

— The system is a whole entity, which yields output Y for the given input X.
— It consists of subsystems (equipment, operators) connected in a series or in parallel, which are also systems.
— The system operates under the control and supervision of one or more persons. Let us call them managerial intermediaries or agents.
— Every agent uses the resources of the system R (equipment, workers) in the system environment E, so that the system generates output Y in a time

ulaza X. Y je tako propusna moć sustava,

- okoliš sustava E (elektroenergetsko postrojenje) skup je nužnih resursa R koji su neograničeni i daleko od svog punog kapaciteta,
- sustavni resursi R pokretni su iz jednog u drugi okoliš sustava E.
- ako je najveći iznos izlaza Y neki I tada se kaže da je propusna moć sustava. I se mjeri u jedinicama izlaza po jedinici vremena. Katkada sustav ima više izlaza, no uvijek se može navesti koji je to glavni izlaz i ostale smatrati manje važnima, nusproizvodima glavnog izlaza. U većini slučajeva ti odnosi su linearno proporcionalni, pa se govori o glavnom proizvodu sustava, npr. od 2 400 MVA·h na dan, te o nusproizvodu od 8 sati rada operatora u sustavu na dan,
- osnovna jednadžba sustava je:

unit from input X. Y is thus the throughput capacity of the system

- The system environment E (electric power facility) is a group of necessary resources R that are unlimited and operating far below their full capacity.
- System resources R are transportable from one system environment E to another.
- If the highest output value is Y, let I be the system throughput capacity. I is measured in output units per unit of time. Sometimes a system has several outputs but it is always possible to state which is the main output and consider the others to be of less importance, secondary products of the main output. In the majority of cases, these relations are linearly proportional. We speak of the main system product, for example of 2 400 MVA·h per day, and of the byproduct of 8 hours of work by the operator in the system per day.
- The basic equation of the system is as follows:

$$I = k \cdot R \,, \tag{1}$$

gdje je:

I — propusna moć sustava,
R — je resurs sustava,
k — je konstanta proporcionalnosti.

Po izrazu (1) propusna moć raste linearno proporcionalno s resursima. Jedinica kvantizacije je B. Sustav dakle posjeduje $n{\cdot}B$ resursa,

- podjela jednog resursa, npr. u vremenu, moguća je ako se jedan resurs koristi u jednom vremenskom intervalu za jednu, a u drugom za drugu namjenu. Označi li se sa S razina podjele resursa, tada je za m mogućih uporaba resursa $S = m - 1$.
- podjela resursa je moguća i u prostoru i u vremenu, naravno, ukoliko takve akcije imaju negativnu interakciju. Propusna moć i razina podjele resursa odnose se kao:

where:

I — system throughput capacity,
R — system resources,
k — proportionality constant.

According to Expression (1), growth in the throughput capacity is linearly proportional to resources. The unit of quantization is B. Thus, the system possesses $n{\cdot}B$ resources.

- Resource sharing, e.g. in time, is possible if a resource is used in one time interval for one purpose and in another time interval for another purpose. If S indicates the level of resource sharing and m indicates the number of the potential uses of the resource, then $S = m - 1$.
- Resource sharing is also possible in space and in time, naturally if such actions have negative interaction. The relation between throughput capacity and the level of the resource sharing is as follows:

$$I = k \cdot R(1 + S) \,, \tag{2}$$

tj. propusna moć raste linearno proporcionalno razini podjele resursa.
Podjela resursa mora se ograničiti maksimalnom mogućom razinom podjele F,

- osnovna jednadžba rizika dana je izrazom preko očekivane propusne moći I (Bradley, James, 2002, [1]):

i.e. throughput capacity increases with linear proportionality to the level of the resource sharing.
Resource sharing must be limited by the maximum possible level of division F.

- The basic risk equation is expressed by the expected throughput capacity I (Bradley, James, 2002, [1]):

$$I' = R \cdot [k + c \cdot r(E) - r(E)] = R \cdot [k + (c-1) \cdot r(E)] , \quad (3)$$

gdje su:

r*(E)* — rizik po jedinici *B* resursa, tj. rizik gubitka propusne moći u ovisnosti u okolišu *E* s obzirom na sustav, a
c — koeficijent učinkovitosti rizika (*c* je konstantan za učinkovit okoliš).

Ulaganja u paralelne resurse, dovode do pretvorbe mogućeg gubitka u izvjesni dobitak.

Osnovno je za svaki rizik odrediti sljedeće parametre:

I — propusna moć,
R — resurs,
k — konstanta propusne moći,
r*(E)* — rizik po jedinici okoliša, tj. mogući gubitak propusne moći u jedinici vremena u sustavu mjeren prema jedinici *B* resursa, a ne prema propusnoj moći sustava. Odatle je r*(E)* srednji očekivani rizik gubitka (*SOG*) jedinice *B* resursa *R*, npr. rizik ozljeđivanja radnika na dan.
S — razina podjele resursa,
c — koeficijent učinkovitosti rizika (*c* ovisi o učinkovitosti okoliša, tako da ukoliko se može dozvoliti povećanje propusne moći, tada se iz tog povećanja može izračunati *c* iz izraza (3)).

Primjenom izraza (2) i (3) dobiva se očekivana propusna moć:

where:

r*(E)* — risk per unit of *B* resource, i.e. the risk of loss in throughput capacity depending on the environment *E* in which the system operates, and
c — risk efficiency coefficient (*c* is constant for the for the efficient environment).

Investment in parallel resources leads to the transformation of potential loss into a certain profit.

For each risk, following basic parameters must be determined:

I — throughput capacity,
R — resource,
k — throughput capacity constant,
r*(E)* — risk per environmental unit, i.e. potential throughput capacity loss in a time unit in the system measured according unit *B* of the resource and not according to the system throughput capacity. Therefore, r*(E)* is the mean expected loss risk (*SOG*) of unit *B* of resource *R*, e.g., the risk of worker injury per day.
S — the level of resource sharing,
c — risk efficiency coefficient (*c* depends on the efficiency of the environment, so that if it is possible to permit increased throughput capacity, from this increased capacity it is possible to calculate *c* from Expression (3)).

Through the application of Expressions (2) and (3), the expected throughput capacity is obtained:

$$I' = R \cdot (1+S) \cdot [k + (c-1) \cdot r(E)] . \quad (4)$$

2.3 Kvalitativni model specifičnog rizika - rizik stradavanja radnika na održavanju

Radnici dolaze u elektroenergetsko postrojenje da obave radove prema planu održavanja. Postoji rizik da se za vrijeme njihovog boravka (A) dogodi kvar, (B) u tom ili susjednim postrojenjima i/ili kvar na uzemljivaču (C), što sve rezultira povećanom opasnošću od ozljeđivanja radnika. Sljedeći su kvalitativni parametri rizika:

— propusna moć *I* je broj radnika koji borave na mjestu rada, čovjek po mjestu rada,
— resurs *R* je sposobnost i znanje radnika,

2.3 Qualitative model of a specific risk – the risk of harm to a maintenance worker

Workers enter an electric power facility to perform work according to the maintenance plan. There is the risk that while they are there (A) a failure will occur,(B) in this or neighboring facilities and/or a fault in the grounding system (C), all of which increases the hazard of worker injury. The following are the qualitative risk parameters:

— throughput capacity *I* is the number of workers who are present at the place of work, person per workplace,
— resource *R* is the ability and knowledge of the workers, their training for work, the total amount

njihova uvježbanost za rad, ukupan iznos svih mogućih, čovjek·sati rada na pojedinom poslu održavanja,

- propusna konstanta k je omjer broja ljudi i njihovih znanja na poslovima održavanja, (čovjek/mjesto rada)/čovjek·sati rada na određenom poslu) = 1/(mjesto rada·sati rada na pojedinom poslu),
- rizik $r(E)$ je rizik gubitka radnika zbog npr. ozljeđivanja u procesu izvođenja radova na održavanju,
- jedinično smanjenje rizika c je povećanje propusne moći (broja radnika) zbog brižljivo izvedenih radova na održavanju, kvaliteta i brzina izvođenja radova, i
- S je mogućnost uporabe pojedinog radnika za vrijeme radnog vremena i u drugim elektroenergetskim postrojenjima, ako posao završe kraće nego što je planirano.

Elektroenergetska se postrojenja mogu s naslova njihova stanja opisati jednim atributom ocjene stanje opreme S_o. Za takav se sustav može izgraditi odgovarajuća shema stanja koja polazi od dekompozicije sustava po principu odozgora-nadolje. Atribut ocjene stanja opreme je trenutačna veličina koja obuhvaća sve komponente sustava i opisuje se jednim brojem između 0 i 1. Stanje $S_o = 0$ odgovaralo bi totalnom nefunkcioniranju sustava (sve neispravno), a stanje $S_o = 1$ savršeno funkcioniranje sustava (sve komponente ispravne). Obično je stanje negdje oko $S_o = 0{,}6$, a kada padne ispod $S_o = 0{,}4$ tada su potrebne znatnije intervencije u njenom održavanju. Ocjena stanja uključuje i neodređenost tako da je njen stvarni opis dan intervalom npr. $S_o = [0{,}55,\ 0{,}59]$.

Zbog jednostavnosti analitičkog pristupa pretpostavit će se stacionarno stanje atributa ocjene stanja opreme te dane granice neodređenosti poznavanja tog stanja.

Isto tako će se pretpostaviti postojanje atributa ocjene stanja vještina radnika na održavanju s pripadnom intervalnom procjenom njenog nepoznavanja $S_{ij} = [0{,}7,\ 0{,}85]$ Neka je i ta procjena i njezina neodređenost stacionarna veličina.

2.4 Učinkovitost okoliša i rizik

Razmatraju se dva okoliša promatranog sustava: E_1 i E_2. Pretpostavlja se da je okoliš E_1 bez rizika pri čemu sustav s resursima R ima stabilni kapacitet $I=k \cdot R$ u jedinici vremena. Okoliš E_2 je isti kao E_1 samo s rizikom. Pretpostavlja se da je propusna moć sustava u E_2 jednaka $k \cdot R + D$ u jedinici vremena uz uvjet da se srećom nije dogodio hazard kojeg se riskiralo (D su rizični dobici). No, kako se u rizičnom okolišu mogu

of all possibilities, man·hours of work on an individual maintenance job,

- throughput constant k is the ratio of the number of people and their knowledge regarding maintenance jobs, (person/workplace)/man·hours of work on a specific job) = 1/(workplace ·hours of work on an individual job),
- risk $r(E)$ is the risk of the loss of a worker due to, for example, injury during the process of performing maintenance work,
- the risk reduction unit c is increased throughput capacity (number of workers) due to carefully performed maintenance work, quality and speed of the performance of the work, and
- S is the possibility of also using an individual worker at other electric power facilities during working hours if a job is completed earlier than planned.

Electric power facilities can be described by an attribute of the assessed state of the equipment S_o. For such a system, it is possible to construct a corresponding diagram that starts from the decomposition of the system according to the top-down principle. The attribute of the assessment of the state of the equipment is the instantaneous value that covers all the system components and is described by a number between 0 and 1. The state $S_o = 0$ would correspond to a totally nonfunctioning system (everything out of order) and the state $S_o = 1$ would correspond to a perfectly functioning system (all the components in good working order). Usually, the state is somewhere around $S_o = 0{,}6$, and when it drops below $S_o = 0{,}4$ significant interventions are necessary regarding its maintenance. Evaluation of the state also includes indeterminacy, so that its actual description is given by an interval, for example $S_o = [0{,}55,\ 0{,}59]$.

Due to the simplicity of the analytical approach, a stationary state of the attributes of the assessment of the state of the equipment and the given limits of indeterminacy regarding knowledge of that state will be assumed.

Similarly, the existence of the attributes of the assessment of the state of the skill of the maintenance workers will be assumed with the corresponding interval of the assessment of the lack of knowledge thereof, $S_{ij} = [0{,}7,\ 0{,}85]$ Let this assessment and its indeterminacy be a stationary value.

2.4 Environmental efficiency and risk

Two environments of the studied system are considered: E_1 and E_2. It is assumed that environment E_1 is without risk, whereby the system with resources R has a stable capacity $I=k \cdot R$ in a time unit. Environment E_2 is the same as E_1 except with risk. It is assumed that the throughput capacity of system E_2 is equal to $k \cdot R + D$ in a unit of time under the condition that with luck the hazard risked has not occurred (D

očekivati i neki gubici G u jedinici vremena u prosjeku, tada je propusna moć sustava jednaka:

are risk gains). However, since in a risk environment some losses G may be expected in a unit of time on average, the throughput capacity of the system is as follows:

$$I = k \cdot R + D - G \; . \tag{4a}$$

Tada su G srednji očekivani gubici (SOG) s obzirom na bez rizični rad s propusnom moći I=$k \cdot R + D$.

Situaciju sa $D > G$ može se smatrati dugoročno ispravnim, a $D < G$ dugoročno neispravnim režimom korištenja okoliša sustava.

Odatle se može zaključiti da su rizik i propusna moć sustava linearno proporcionalne veličine.

Najveći omjer D/G koji se može postići u nekom okolišu naziva se koeficijent učinkovitosti c. Uvede li se zamjena $c - 1$ ($c - 1 = b$) u izraz (4) dobiva se često korišteni oblik jednadžbe propusne moći sustava:

Then G stands for the mean expected losses (SOG) regarding no-risk operation with a throughput capacity of I=$k \cdot R + D$.

The situation with $D > G$ can be considered as justified over the long term, and $D < G$ can be considered as an unjustified regime over the long term use of the environment system

Therefore, it may be concluded that the risk and throughput capacity of the system are linearly proportional values.

The highest ratio of D / G that can be achieved in an environment is called the efficiency coefficient c. If b is substituted for $c - 1$ ($c - 1 = b$) in Expression (4), a frequently used form of the equation is obtained for the throughput capacity of a system:

$$I' = R \cdot [k + b \cdot r(E)] \, , \tag{5}$$

koji se rabi u financijama i gdje je:

R — ukupno uložena suma,
k — garantirana kamata,
$b \cdot r(E)$ — jedinična ekstra dobit za rizično ulaganje.

Primjer
Za tehnički sustav koji se promatra, a koji je dio DP Elektroslavonija Osijek za grad Osijek, organizacijska jedinica Pogon Osijek sa jedinom zadaćom održavanja elektroenergetskog postrojenja vrijedi:

300 trafostanica 35/10 kV (10 kom) i 10/0,4 kV (290 kom), sa 140 radnika na održavanju i s prosječno 12 sati rada po svakoj trafostanici godišnje (iz istraživanja vremena održavanja).

Iz toga slijedi:

$R = 300 \cdot 12 = 3600$ čovjek·sati i
$I = 140$ radnika, pa je
$k = 0{,}038\ 888$ jedinica resursa R po godini u nerizičnoj situaciji.

which is used in finances and where:

R — the total sum invested,
k — guaranteed interest,
$b \cdot r(E)$ — unit of extra profit for risk investment.

Example
For the technical system considered, the following apply for the organizational unit Pogon Osijek, which is a part of the distribution territory DP Elektroslavonija Osijek for the city of Osijek and has the sole task of maintaining the electrical power facilities:

300 substations, of which 10 are 35/10 kV and 290 are 10/0,4 kV, with
140 maintenance workers and an average of
12 man·hours of maintenance work per substation annually (from a study of maintenance time).

Therefore:

$R = 300 \cdot 12 = 3600$man·hours and
$I = 140$ workers, and thus
$k = 0{,}038\ 888$resource unit R per year in a non-risk situation

Iz istraživanja povreda na radu proizlazi 36 povreda od električne energije u 30 godina, što iznosi 1,166 66 povreda godišnje, ili u relativnom iznosu oko 0,002.

Ako se ustanovi učinkoviti okoliš E s takvim, upravo navedenim srednjim očekivanim gubitkom (rizikom gubitka radnika) $SOG = 0{,}002$ jedinice po godini, onda povećanje propusne moći na 150 jedinica traži:
$I' = 3\,600(0{,}038\,888 + x) = 150,$
Odatle:
$x = b \cdot r(E) = 0{,}002\ SOG\ b = 0{,}002\,778\,6,$
pa je:
$b = 1{,}389\,3$ ili $c = 2{,}389\,3.$

Najveća propusna moć bit će $3600 \cdot (0{,}038\,888 + 2{,}389\,3 \cdot 0{,}002) = 157{,}2$ čovjek·sati. Pitanje je kako će se pokazati najmanja propusna moć.

2.5 Numerički pokus određivanja jednostavnog rizika

Niz podataka za sustav S dan je kao slučajna veličina s podacima obrađivanog sustava.
Za izračun jednostavnog rizika kod procesa održavanja potrebno je poznavati sljedeće podatke:

resurs R — ukupan broj raspoloživih čovjek·sati svih ekipa za održavanje,
propusna moć I — potreban broj ekipnog rada na održavanju sustava izražen kao potrebni čovjek·sati.

Neka se zamisli stanje Pogona Osijek kod održavanja distribucijskog sustava grada Osijeka koje se može realizirati u periodu od 10 godina, a želi se povećanje resursa za 50 jedinica godišnje. Pri tome se pretpostavlja povećanje broja radnika u svakoj godini.

From a study of worker injuries, it was shown that there were 36 injuries from electricity in *30* years, which amounts to 1,166 66 injuries, or a relative figure of approximately 0,002.

If the efficient environment E is established with the aforementioned mean expected loss (the risk of worker loss) $SOG = 0{,}002$ units per year, then the increased throughput capacity to 150 units requires the following:
$I' = 3\,600(0{,}038\,888 + x) = 150,$
from which:
$x = b \cdot r(E) = 0{,}002 \cdot b = 0{,}002\,778\,6,$
and thus:
$b = 1{,}389\,3$ ili $c = 2{,}389\,3.$

The greatest throughput capacity will be $3600 \cdot (0{,}038\,888 + 2{,}389\,3 \cdot 0{,}002) = 157{,}2$. The question is how the minimum throughput capacity will be represented.

2.5 Numerical test to determine simple risk

A series of data for system S is given as a random value with data from the system considered.
For the calculation of the simple risk in the process of maintenance, it is necessary to know the following information:

resource R — the total number of available man hours. of all the maintenance teams,
throughput capacity I — the man·hours of system maintenance teams required.

Let us imagine the state of the Osijek plant regarding the maintenance of the distribution system of the city of Osijek which can be achieved within a period of 10 years, and it is desired to increase resources by 50 units annually. An increased number of workers is assumed for each year.

Tablica 1 — Numerički primjer
Table 1 — Numerical example

Redni broj / Ordinal No.	Ukupan broj raspoloživih ekipa (čovjek·sati/god) / Total number of available teams (man-hours/year) R resurs / resource	Potreban broj radnika (čovjek·sati) / Required number of workers (man-hours) I propusna moć / throughput capacity
1	3 450	140 diff =–10
2	3 500	142 diff = –8
3	3 550	145 diff = –5
4	3 600	148 diff = –2
5	3 650	149 diff = –1
6	3 700	151 diff = 1
7	3 750	152 diff = 2
8	3 800	155 diff = 5
9	3 850	158 diff = 8
10	3 900	160 diff = 10
	Ukupno / Total 36 750	Ukupno / Total 1 500 diff abs. = 52

diff – razlika / difference
abs – apsolutna (vrijednost) / absolute (value)
int – cijeli broj / integer

Ako se pretpostavi planirani resursni kapacitet 3800 čovjek·sati, i planiranu propusnu moć za 10 godina na 150 čovjek·sati, planirani je koeficijent resursa je 150/3 800 = 0,039 473 6.

Izračun srednjeg očekivanog gubitka *SOG* za proces na tablici je prema izrazu:

If a planned resource capacity of 3800 man·hours and a throughput capacity for 10 years of 150 man·hours are assumed, the planned resource coefficient is 150/3 800 = 0,039 473 6.

The calculation of the mean expected loss *SOG* for the process on the table is according to the expression:

$$SOG = \sum_{n} diff(\text{int})_{\text{abs}} \,, \tag{6}$$

gdje je razlika interventnih radova računata prema srednjem broju intervencija, a n je broj perioda računanja, godina.

Iz gornjih podataka izlazi da je SOG = 5,2. Izračun $r(E)$ zasnovan je na omjeru SOG i resursnog kapaciteta i iznosi $r(E)$ = 5,2/3 800 = 0,001 368 4.

Primjena jednadžbe rizika, izraz (3), daje uz pretpostavljeni c = 1,25, I' = 3 675 · (0,039 473 6 + 0,25 · 0,001 368 4)=144,17 propusnu moć čovjek·sati/god. što je manje od planiranih 150 čovjek·sati/god.

Sa:
c = 1,5 I' = 147,58 čovjek·sati/god.,
c = 1,75 I' = 148,84 čovjek·sati/god.,
c = 2 I' = 150,09 čovjek·sati/god., te
c = 2,25 I' = 151,35 čovjek·sati/god., što bi bila maksimalna vrijednost propusne moći.

Srednja razlika je 151,35 – 147,58 = 3,77 čovjek·sati/god.
Najveća dozvoljena srednja razlika bi bila dvostruka vrijednost, tj. 7,54 čovjek·sati/god.
Vjerojatni minimum protočne moći, tj. radnika bi tako bio 151,35 – 7,54 = 143,81, tj. 143 čovjek·sati/god.

Slike 2 do 4 pokazuju međusobne odnose rizika, resursa te propusne moći.

where the difference in the intervention work is calculated according to the mean number of interventions and n is the number of the calculation periods, years.

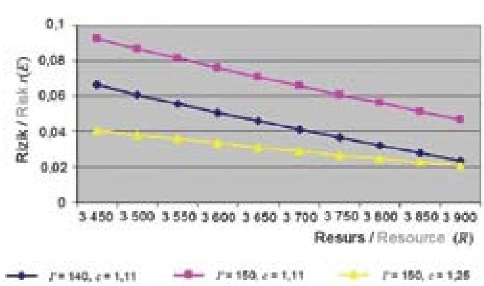
From the above data, it follows that SOG = 5,2. The calculation of $r(E)$ is based upon the ratio of the SOG and the resource capacity, amounting to $r(E)$ = 5,2/3 800 = 0,001 368 4.

Application of the risk equation, Expression (3), under the assumption c = 1,25, I' = 3 675 · (0,039 473 6 + 0,25 · 0,001 368 4)=144,17 yields throughput capacity man·hours/year, which are fewer than the planned 150 man·hours/year

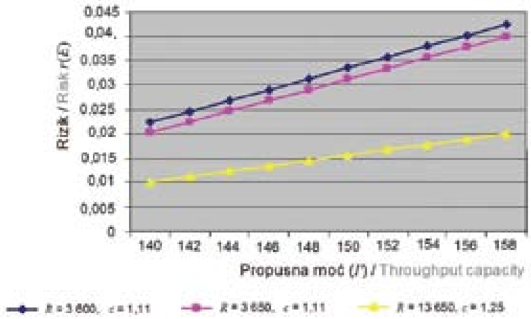
with:
c = 1,5 I' = 147,58 man·hours/year,
c = 1,75 I' = 148,84 man·hours/year,
c = 2 I' = 150,09 man·hours/year, and
c = 2,25 I' = 151,35 man·hours/year, which would be the maximum throughput capacity value.

The mean difference is 151,35 – 147,58 = 3,77 man·hours/year
The maximum permitted difference would be twice this value, i.e. 7,54 man·hours/year
The probable minimum throughput capacity, i.e. workers, would then be 151,35 – 7,54 = 143,81, i.e. 143 man·hours/year

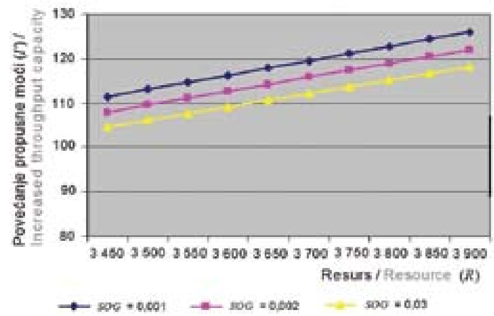
Figures 2 to 4 present the relations among risks, resources and throughput capacity.



Slika 2 — Odnos rizika i resursa
Figure 2 — Risk/Resource Ratio



Slika 3 — Odnos rizika i propusne moći
Figure 3 — Risk/Throughput capacity ratio



Slika 4 — Odnos povećanja propusne moći i resursa
Figure 4 — Increased throughput capacity/resource capacity

3 VJEROJATNOSTNA METODA ODREĐIVANJA RIZIKA

Vjerojatnost da se radnik nalazi na poslovima održavanja (komponenta A – prema istraživanju vremena potrebnog za održavanje) u trafostanici 35/10 kV je:

$P_{35/10}$(A)= 66,08/8 760 = 0,007 54 po trafostanici i godini, a kako ih je 10 to je vjerojatnost boravka u bilo kojoj 0,075 4,

dok je u TS 10/0,4 kV:

$P_{10/0,4}$(A)= 10,41/8 7600 = 0,001 19 po godini i jednoj TS, a kako ih je 290 to je vjerojatnost boravka u bilo kojoj 0,345 1.

Vjerojatnost da je kvar u postrojenju za vrijeme radnog vremena od 7:00 do 15:00 sati (komponenta B prema istraživanju kvarova sa zemljom u postrojenju) je:

P(B)=48 %.

Vjerojatnost da je pri tom djelomični kvar uzemljivača (komponenta C prema istraživanju pouzdanosti uzemljivača) je od P(C)=0,1 % (osnovni uzemljivač), preko 1,85 % (uzemljivač mreže niskog napona) do 2,4 % (uzemljivač susjednih TS preko VN kabela).

Stoga nastupaju rizične situacije za stradavanje radnika:

a) Radnik se nalazi u postrojenju na poslovima održavanja, vjerojatnost situacije 0,075 4 za TS 35/10 kV, a 0,345 1 za TS 10/0,4 kV.

3 THE PROBABILITY METHOD OF RISK ASSESSMENT

The probability that a worker will find himself on a maintenance assignment (component A – according to a study on the time required for maintenance) in a 35/10 kV substation is:

$P_{35/10}$(A)= 66,08/8 760 = 0,007 54 per substation per year, and since there are 10 of them the probability of being in any of them is 0,075 4,

while in a 10/0,4 kV substation it is

$P_{10/0,4}$(A)= 10,41/8 7600 = 0,001 19 per year per substation. Since there are 290 of them, the probability of being in any one of them is 0,345 1.

The probability of a failure in a facility during working hours from 7 a.m. to 3 p.m. (component B – according to a study of ground faults in the facilities) is as follows:

P(B)=48 %.

The probability that a partial failure of a grounding system would occur then (component C – according to a study on the reliability of grounding electrodes) is P(C)=0,1 % (main grounding electrode), 1,85 % (grounding electrode of a low voltage network) up to 2,4 % (grounding electrode of neighboring substations via a high voltage cable).

Therefore, risk situations for injury to workers are as follows:

a) A worker finds himself at a facility on a maintenance job, the probability of the situation is 0,075 4 for a 35/10 kV substation and 0,345 1 for a 10/0,4 kV substation.

b) Vjerojatnost situacije da se upravo u tom trenutku dogodi kvar je $0{,}48 \cdot 0{,}075\,4 = 0{,}036\,2$ za TS 35/10 kV, a $0{,}48 \cdot 0{,}345\,1 = 0{,}166$ za TS 10/0,4 kV,

c) Vjerojatnost situacije da se u tom intervalu vremena imamo i djelomični kvar na uzemljivaču $0{,}036\,2 \cdot 0{,}001 = 0{,}000\,036\,2$ za TS 35/10 kV, a $0{,}166 \cdot 0{,}001 = 0{,}000\,166$ za TS 10/0,4 kV.

Slijedi tablica matematičkih vjerojatnosti svih mogućih opasnih stanja u kojem se mogu naći radnici distribucije za vrijeme normalnog svakidašnjeg rada.

b) The probability of a situation that a fault occurs precisely at that instant is $0{,}48 \cdot 0{,}075\,4 = 0{,}036\,2$ for a 35/10 kV substation and $0{,}48 \cdot 0{,}345\,1 = 0{,}166$ for a 10/0,4 kV substation.

c) The probability of a situation that in that time interval we also have a partial failure of the grounding system is $0{,}036\,2 \cdot 0{,}001 = 0{,}000\,036\,2$ for a 35/10 kV substation and $0{,}166 \cdot 0{,}001 = 0{,}000\,166$ for a 10/0,4 kV substation.

The table presents the mathematical probabilities for all the possible hazardous states in which distribution workers can find themselves during normal daily working hours.

Tablica 2 — Matematičke vjerojatnosti rizika
Tablica 2 — Mathematical risk probability

Redni broj / Ordinal no.	Vjerojatnosti / Probabilities				
	Prisutnost radnika (A) / Worker presence (A)			Istodobna pojava kvara (A+B) / Simultaneous occurrence of fault (A+B) (2·0,48)	Istodobna pojava i djelomičnog kvara na uzemljivaču postrojenja slučaj (A+B+C) / Simultaneous occurrence of a partial failure of the grounding system of the facility in the event of (A+B+C) a – osnovni uzemljivač 0,001 / a – main grounding electrode 0,001 b – uzemljenje preko kabela visokog napona 0,024 / b – grounding via a high voltage cable 0,024 c – uzemljenje preko mreže niskog napona, 0,0185 / grounding via a low voltage network 0,0185 ab – 9,78E · 06 ac – 1,07E · 05 bc – 3,25E · 04 (2·3·(a ili / or b ili / or c ili / or ab ili / or ac ili / or bc))
	TS 35/10 kV · za / for 10 TS	TS 10/0,4 kV · za / for 290 TS	Prosječno obje TS/2 / Mean for both substations/2		
1	2			3	4
1a	0,075 4			3,62E · 02	3,62E · 05
1b	0,075 4			3,62E · 02	8,69E · 04
1c	0,075 4			3,62E · 02	6,70E · 04
1ab	0,075 4			7,37E · 07	7,21E · 12
1ac	0,075 4			3,62E · 02	3,87E · 07
1bc	0,075 4			3,62E · 02	1,18E · 05
2a		0,345 1		1,66E · 01	1,66E · 04
2b		0,345 1		1,66E · 01	3,98E · 03
2c		0,345 1		1,66E · 01	3,06E · 03
2ab		0,345 1		1,66E · 01	1,62E · 06
2ac		0,345 1		1,66E · 01	1,77E · 06
2bc		0,345 1		1,66E · 01	5,38E · 05
3a			0,210 25	1,01E · 01	1,01E · 04
3b			0,210 25	1,01E · 01	2,42E · 03
3c			0,210 25	1,01E · 01	1,87E · 03
4ab			0,210 25	1,01E · 01	9,87E · 07
4ac			0,210 25	1,01E · 01	1,08E · 06
4bc			0,210 25	1,01E · 01	3,28E · 05
5					

Usporedba izračuna rizika stradavanja radnika distribucije na poslovima održavanja:

— iskustveni podatak iz prakse: 0,002,
— rezultat Bradley metode: 0,001 368 4,
— rezultati vjerojatnostne metode: 0,001 87; 0,002 4; 0,003 06; 0,003 98.

Comparison of the risk calculations of injury to a distribution worker engaged in maintenance work:

— data from practical experience: 0,002,
— result of the Bradley method: 0,001 368 4,
— results of the probability method: 0,001 87; 0,002 4; 0,003 06; 0,003 98..

4 FINANCIJSKE VELIČINE

Rizik gubitka radnika ozljeđivanjem ili smrću stalno je prisutan još od trenutka, po pozitivnim propisima, kada krene na posao. Stoga je i novčana naknada za izgubljeno zdravlje ili život prisutna i dosta realna. Poslovodstvo tvrtke može bitno utjecati na opasnosti za zdravlje i život unutar radnog procesa. U ovom radu se posebno razmatra rizik od ozljeda na radu tijekom planiranog rada na održavanju distribucijskog elektroenergetskog sustava, i to posebno promatrajući rizike gubitka radnika od udara električne energije.

Stoga se krenulo s istraživanjem ozljeda na radu te je napravljena baza podataka svih ozljeda na radu u DP Elektroslavonija Osijek iz koje je posebno izdvojena Tablica podataka s nezgodama na radu na području grada Osijeka. Tu su izdvojene sve povrede koje uključuju djelovanje električne energije na tijelo radnika, sa svim relevantnim podacima gdje, kada i kako su se dogodile. Iz te tablice slijedi da su rizici gubitka radnika samo od takvih potencijalno opasnih događaja oko 0,2 %.

Sljedeće istraživanje je provedeno stvarajući bazu podataka svih kvarova koji su se dogodili na području grada Osijeka na postrojenjima srednjeg napona tijekom kojih je u pogonskim dnevnicima dispečera ostala zabilješka o isključenju radi djelovanja zaštite ili zemljospojne, ili od jednopolnog ili višepolnog kvara sa zemljom. Tu su se evidentirali svi relevantni podaci o tom događaju uključujući i vrijeme događanja. Analiza pokazuje da se 48 % svih takvih kvarova događa baš u djelatno radno vrijeme, tj. od 7:00 do 15:00 sati. To sigurno djeluje na rizike gubitka radnika povećavajući ga, a zbog mogućeg kontakta s električnom energijom u trenutku kvara.

O vremenu, koje radnici provode na poslovima održavanja u postrojenjima distribucije, a prema važećem Pravilniku o održavanju elektrodistribucijskih objekata i postrojenja, napravljeno je posebno istraživanje. Ono pokazuje da se vremenski najviše radnici zadržavaju u TS 35/10 kV (66 sati po radniku i trafostanici godišnje) i u TS 10/0,4 kV (10,42 sata po radniku i trafostanici godišnje). Uvažavajući broj trafostanica jasno je da potencijalno opasni događaji s velikom strujom kroz uzemljivač bitno povećavaju rizike.

Financijske veličine troškova uzrokovanih povredama na radu, pogotovo vezanih na kontakt s električnom energijom, bilo je vrlo teško skupiti i analizirati, jer se u tvrtki do sada nisu sustavno vodile takve evidencije. To pokazuje kako se

4 FINANCIAL VALUES

The risk of the loss of a worker due to injury or death is constantly present from the moment, according to positive regulations, when the worker goes to work. Therefore, financial compensation for the loss of health or life is present and a realistic consideration. Company management can significantly affect the hazards to health and life within the working process. In this article, risk to a worker during planned maintenance work on an electric power system is specifically discussed, especially regarding the risks of worker loss due to electrical shock.

Therefore, this study began with an investigation of injuries at work. A database was prepared of all the work-related injuries at DP Elektroslavonija Osijek, from which the table data were taken on accidents at work in the area of the city of Osijek. All the injuries were entered that included the effect of electricity on the body of a worker, with all the relevant data, when and how they happened. From this table, it follows that the risk of worker loss solely due to such potentially hazardous events is approximately 0,2 %.

The study was conducted by creating a database of all the failures that occurred in the territory of the city of Osijek at medium voltage facilities during which there were notes in the dispatchers' log books on switching off due to protection tripping or ground faults, or from single-phase or multi-phase ground faults. All the relevant data are entered here on these events, including the times of the events. Analysis shows that 48 % of all such failures occur precisely during working hours, i.e. from 7 a.m. to 3 p.m. This certainly has an effect on the risk of worker loss, increasing it, and due to potential contact with electricity at the moment of the failure.

Regarding the time that the workers spend on maintenance tasks at the distribution facilities and according to the current Regulations on the Maintenance of Electrical Distribution Facilities and Plants, a separate investigation was conducted. It demonstrated that workers spend the most time at 35/10 kV substations (66 hours per worker and substation annually) and at 10/0,4 kV substations (10,42 hours per worker and substation annually). Taking the number of substations into account, it is clear that potentially dangerous events with high fault current flowing through the grounding electrode significantly increase risks.

The financial costs incurred due to injury at work, especially in connection with contact with electricity, were very difficult to collect and analyze because until now such evidence had not been recorded systematically in the company. This shows that until now this company has not paid much attention to instruments for the reduction of such types of financial expendiova kompanija, do sada, nije previše bavila instrumentima za smanjivanje takvih vrsta financijskih troškova. Neki odgovorni ljudi tvrtke osjećaju postupno povećanje te vrste troškova te uviđaju da će ubrzo morati sustavno i daleko češće i kvalitetnije pratiti i procjenjivati takve novčane odljeve radi boljeg poslovanja tvrtke.

U slučajevima povreda na radu radnika distributivne tvrtke, ali i za radnike drugih tvrtki i ostale prolaznike u blizini elektroenergetskih distribucijskih postrojenja, tvrtka je vezana objektivnom odgovornošću zbog dvije činjenice:

— kao imatelj opasne tvari i
— jer se bavi opasnom djelatnošću.

Tu odgovornost isključuje samo:

— viša sila,
— djelovanje treće osobe i
— gruba nepažnja oštećenoga.

Naravno da je potrebno dokazati takvo isključenje što se u sudskoj praksi pokazalo gotovo nemoguće.

U nastavku je dana tablica svih podataka koji su mogli biti prikupljeni, prezentirani i analizirani.

tures. Some responsible people in the company feel that there has been a gradual increase in these types of expenditures and are of the opinion that it will soon be necessary to monitor and assess such monetary outflows systematically and far more often in order to improve company performance.

In cases of worker injuries at distribution companies, but also for workers of other companies and passersby in the vicinity of an electrical distribution facility, a company is objectively liable due to two facts:

— it is the owner of hazardous materials and
— it is engaged in a hazardous activity.

Such liability excludes only the following:

— force majeure,
— the activities of a third person and
— gross negligence of the injured party.

Naturally, it is necessary to prove such exclusions, which in court practice has been shown to be practically impossible.

The table below presents all the data that could be collected, presented and analyzed.

Tablica 3 – Financijske veličine
Table 3 – Financial values

	Uzrok bolovanja / Reason for sick leave	Godina / Year				
		2002.	2003.	2004.	2005.	2006.
Isplaćeno / Amount paid [HRK]	Bolest / Illness	807 949,55	935 791,82	975 232,90		
	Povreda na radu / Injury at work	257 647,42	195 946,20	161 895,44	215 751,84	162 915,56
	Porodiljni / Parental leave	115 370,38	0,00	0,00		
	Njega / Care	48 120,20	43 808,95	38 275,25		
Dani bolovanja / Days of sick leave	Bolest / Illness	4 481	4 406	4 214		
	Povreda na radu / Injury at work	1 177	778	584	572	416
	Porodiljni / Parental leave	879	748	1 008		
	Njega / Care	342	313	339		
Broj slučajeva / Number of cases	Bolest / Illness	421	430	412		
	Povreda na radu / Injury at work	25	45	26	29	21
	Porodiljni / Parental leave	6	9	2		
	Njega / Care	73	54	50		

Na financijske troškove tvrtke nastale zbog povreda na radu, s posebnim naglaskom na povrede s uključenim djelovanjem električne energije, utječu:

— bolovanja,
— troškovi izvođača radova drugih tvrtki na održavanju zbog izostanka radnika,
— naknade imovinske i neimovinske štete,
— troškovi liječenja,

The following influence the financial expenditures of the company that occur due to injury at work, with particular emphasis on injuries that include the effect of electricity.

— sick leave,
— labor costs for maintenance workers from other companies due to worker absence,
— compensation for pecuniary and non-pecuniary damages,

- troškovi zbog kaznene prijave inspektora zaštite na radu,
- troškovi zbog nezgode na radu preko osiguravatelja,
- i drugi direktni i indirektni troškovi, kao npr. troškovi doživotne rente,
- u slučaju smrtne posljedice pojavljuju se troškovi naknade imovinske i
- neimovinske štete koja, po trenutačnoj sudskoj praksi, iznosi do 250 000,00 HRK po članu obitelji oštećenoga.

5 ZAKLJUČAK

Promatrajući samo financijske elemente troškova povreda na radu u Elektroslavoniji Osijek, mogu se formirati sljedeći zaključci:

Kao maksimalna veličina pojavljuje se trošak bolovanja od 10 306,00 HRK po radniku godišnje što pomnoženo s prosječno 30 radnika na bolovanju godišnje iznosi 309 180,000 HRK.

Procjena troškova zbog izostanka radnika s posla pokazuje da je izgubljeno prosječno 705 radnih dana koje bi (ako se na tim poslovima unajme radnici druge tvrtke) trebalo platiti dodatnih gotovo 300 000,00 HRK godišnje.

Treba računati da će troškovi na ime doživotne rente i troškova liječenja, koji su sada oko 150 000,00 HRK godišnje, rasti na veće vrijednosti.

Ako je procjena da se svakih 5 godina dogodi povreda sa smrtnom posljedicom, tada za prosječno 3 člana obitelji na ime naknada imovinske i neimovinske štete treba isplatiti oko 150 000,00 HRK godišnje.

Ukupno svi ti troškovi se mogu procijeniti na 1 000 000,00 HRK po godini što je 33 000,00 HRK po radniku godišnje. Ako se tu posebno izdvoje ozljede na radu nastale kao posljedica djelovanja električne energije i pretpostavi samo dvije takve ozljede godišnje, tada se može reći da bi u tom slučaju ukupni troškovi bili do 200 000,00 HRK po radniku godišnje, s tendencijom strmog uzlaznog rasta.

Većina ovih troškova rast će i unatoč poduzetim mjerama za smanjenje troškova ozljeđivanja radnika, no ako se troškove rizika ugroze radnika na održavanju ne stavi pod kontrolu, za očekivati je eksplozivan rast, jer postrojenja nisu održavana dugo vremena i ulaganja u njih nisu bila dostatna.

- costs of medical treatment,
- costs due to penalties imposed by the work safety inspector,
- costs due to accidents at work via an insurer, and
- other direct and indirect costs, such as costs for life-long financial support.
- in the event of fatal consequences, there are costs for compensation for pecuniary and non-pecuniary damages which, according to current court practice, can be up to 250 000,00 HRK per family member of the deceased.

5 CONCLUSION

Considering only the financial costs of work-related injuries at Elektroslavonija Osijek, it is possible to draw the following conclusions:

The greatest expenditure is the cost of sick leave, 10 306,00 HRK per worker annually, which when multiplied by an average of 30 workers on sick leave annually amounts to 309 180,000 HRK.

Assessment of the costs due to worker absence from work shows that an average of 705 working days are lost for which, if workers from other companies are engaged to do these jobs, it is necessary to pay nearly an additional 300 000,00 HRK annually.

It is necessary to take into account that costs for lifelong support and medical treatment, which are currently approximately 150 000,00 HRK annually, will rise.

If it is estimated that every 5 years there will be an injury with fatal consequences, then for an average 3-member family it will be necessary to pay approximately 150 000,00 HRK annually for pecuniary and non-pecuniary damages.

All the expenditures together can be estimated at 1 000 000,00 HRK per year, which is 33 000,00 HRK per worker annually. If work injuries are singled out that occurred as a consequence of the effect of electricity and only two such injuries annually are assumed, then in such a case the total costs would be up to 200 000,00 HRK per worker per year, with a tendency toward sharp increase.

Despite the measures undertaken for reducing the costs of worker injuries, the majority of the costs will rise. However, if the costs of the risks to maintenance workers is not subject to control, explosive growth can be expected because the facilities have not been serviced for a long time and investments in them have not been sufficient.

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NAPON NUL-VODIČA MREŽE NISKOG NAPONA ZA VRIJEME ZEMLJOSPOJA U MREŽI SREDNJEG NAPONA

THE NEUTRAL CONDUCTOR VOLTAGE IN A MEDIUM-VOLTAGE NETWORK DURING A GROUND FAULT

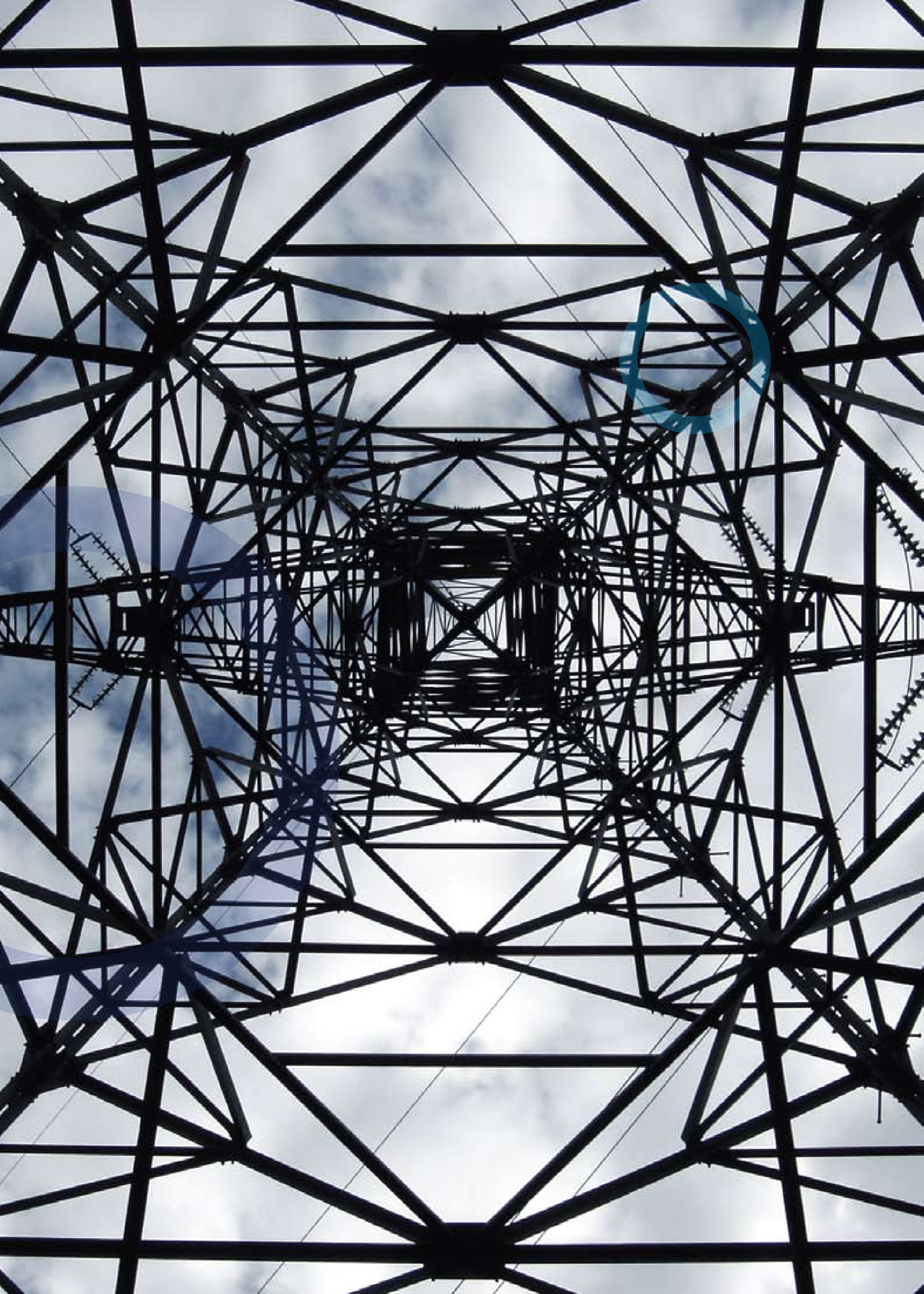
Matislav Majstrović, Zagreb, Hrvatska – Hrvoje Olujić, Split, Hrvatska

Od svih zemljospojeva koji se mogu pojaviti u mrežama srednjeg napona sa stanovišta sigurnosti ljudi i opreme najproblematičniji je zemljospoj u trafostanici srednji napon/niski napon. Naime, uzemljivački sustav mreže niskog napona direktno je povezan s uzemljivačem trafostanice. Stoga se svako povećanje potencijala uzemljivača trafostanice direktno prenosi preko nul-vodiča u instalaciju potrošača. Iz navedenih razloga u ovom radu detaljnije se obrađuje problematika određivanja napona nul-vodiča u mreži niskog napona za vrijeme zemljospoja na razini srednjeg napona u pojnoj trafostanici koja je element mreže srednjeg napona s izoliranim zvjezdištem. Prezentiran je računski model za analizu napona nul-vodiča u realnim distribucijskim mrežama. Analizirane su dvije karakteristične distribucijske mreže položene na kraškom terenu. Dobiveni rezultati su uspoređeni s rezultatima mjerenja.

Of all the ground faults that can occur in medium-voltage networks from the standpoint of human and equipment safety, the most problematic is a ground fault in a medium-voltage/low-voltage substation. The grounding system of a low-voltage network is directly connected to the grounding electrode of the substation. Therefore, each increase in the potential of the grounding electrode of the substation is transmitted directly via the neutral conductor into the customer's installation. For these reasons, in this article a detailed investigation is presented of the problem of determining the neutral conductor voltage in a low-voltage network during a ground fault at the medium-voltage level in a supply substation that is an element of a medium-voltage network with an isolated neutral point (star point). A computer model is presented for the analysis of the neutral conductor voltage in actual distribution networks. Two characteristic distribution networks located on karstic terrain are analyzed. The results obtained are compared to the results of measurements.

Ključne riječi: distribucijska mreža, napon nul-vodiča, niski napon, potencijal, srednji napon, zemljospoj

Key words: distribution network, ground fault, low-voltage, medium-voltage, neutral conductor voltage, potential

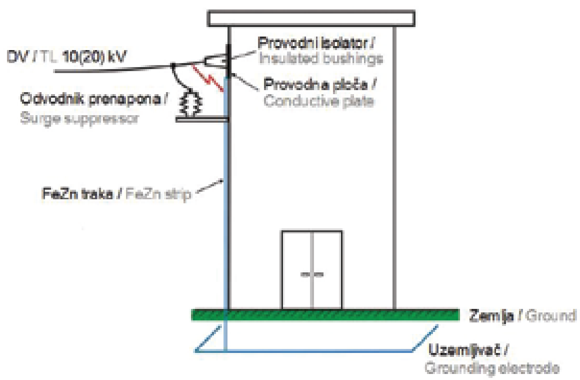


1 UVOD

Distribucijske trafostanice srednji napon/niski napon ((TS SN/NN) široko su rasprostranjeni objekti. Prema zadnjim dostupnim tehničkim podacima na području HEP Operator distibucijskog sustava (HEP ODS), Distribucijsko područje (DP) Elektrodalmacija Split u pogonu je 2 541 TS 10(20)/0,4 kV, od kojih je 2 232 u vlasništvu Hrvatske elektroprivrede (HEP d.d.), a ostale su u vlasništvu drugih pravnih subjekata. Za ilustraciju slika 1 prikazuje TS 10(20)/0,4 kV tipa tornjić na koju je preko provodnih izolatora priključen 10(20) kV zračni vod. Provodna ploča na koju se učvršćuje provodni izolator najčešće je metalna i uzemljena. Probojem provodnog izolatora u jednoj fazi događa se zemljospoj.

1 INTRODUCTION

Medium-voltage/low-voltage distribution substations are widespread. According to the most recent available technical data, within the territory of the HEP Distribution System Operator (HEP ODS), Distribution Region (DP) Elektrodalmacija Split, there are 2 541 10(20)/0,4 kV substations in operation, of which 2 232 are owned by HEP d.d. (Hrvatska elektroprivreda – The Croatian Power Company) and the remaining are under the ownership of other legal subjects. As an illustration, Figure 1 shows a 10(20)/0,4 kV substation to which a 10(20) kV aerial line is connected using insulated bushings. The conductive plate to which the insulated bushings are fastened is most often metal and grounded. A ground fault can occur due to the breakdown of an insulated bushing in a single phase.



Slika 1 — TS 10(20)/0,4 kV tipa tornjić
Figure 1 — 10(20)/0,4 kV substation

Slično vrijedi i za ostale tipove trafostanica koji se pojavljuju u distribucijskoj praksi. U slučaju spomenutog zemljospoja uzemljivač pogođene trafostanice dolazi na puni potencijal kvara i taj se potencijal preko nul-vodiča, koji je vezan za uzemljivački sustav ove trafostanice prenosi do instalacija niskog napona potrošača. Potencijal nul-vodiča u instalaciji potrošača ovisi o više faktora, ovisno o tome napaja li se potrošač podzemnim kabelom niskog napona uz položeno uzemljivačko uže ili traku ili se napaja zračnim vodom (samonosivim kabelskim snopom SKS ili golim vodičima). Pri tom kod napajanja zračnim vodom potencijal nulvodiča najviše ovisi o tome na koliko je stupnih mjesta nul-vodič uzemljen duž izvoda i koliko su kvalitetno izvedeni uzemljivači tih stupova.

U ovom radu analiziraju se razni slučajevi prenošenja potencijala u mrežu niskog napona pri zemljospoju u neuzemljenoj mreži srednjeg napona na kraškom terenu, gdje specifični otpor zemlje znatno ovisi o vremenskim prilikama

The same also applies to the other types of substations in distribution practice. In the event of a ground fault, the grounding electrode of the affected substation reaches fault potential. This potential is transferred via the neutral conductor, which is connected to the grounding system of the substation, to the customer's low-voltage installation. The neutral conductor potential in the customer's installation depends on several factors, according to whether the customer is supplied via a low-voltage underground cable together with a grounding cable or a grounding strip or is supplied via an aerial line (aerial bundled conductors or bare conductors). When supplied via an aerial line, the neutral conductor voltage primarily depends upon the number of pole sites at which the neutral conductor is grounded along the feeder and the quality of the installation of the grounding electrodes of the poles.

In this article, various cases of the transfer of potential in a low-voltage network during ground faults in an ungrounded medium-voltage network on karstic terrain are analyzed, where the specific soil resis-

(padalinama). Za primjer odabrane su dvije distribucijske mreže DP-a Elektrodalmacija Split kod kojih su mreže 10(20) kV u pogonu s izoliranim zvjezdištem. Analiza je provedena za dva karakteristična vremenska razdoblja (vlažni i suhi). Rezultati dobiveni računskim putem uspoređeni su s rezultatima dobivenim mjerenjem na terenu.

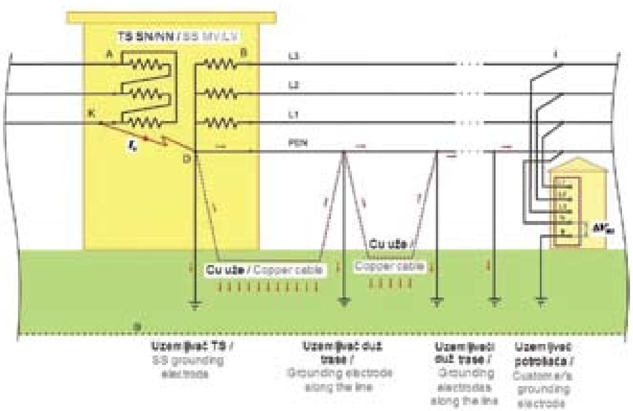
tivity significantly depends upon the weather conditions (precipitation). As an example, two distribution networks have been chosen within DP Elektrodalmacija Split, where 10(20) kV networks are in operation with isolated neutral points. Analysis was performed for two characteristic seasons of the year (rainy and dry). The results obtained by computer are compared to the results obtained from measurements on the terrain.

2 PRORAČUN STRUJE ZEMLJOSPOJA

Napajanje TS SN/NN izvodi se kabelskim i/ili zračnim vodovima srednjeg napona. Kabelski vodovi izvode se najčešće kabelima čiji su metalni plaštevi uzemljeni u pripadnim trafostanicama. Paralelno sa svakim kabelom polaže se uzemljivačko uže ili traka. U ovom radu, radi preglednosti postupka, najprije će se analizirati zemljospoj u neuzemljenoj mreži srednjeg napona sa zračnim vodovima bez dozemnog užeta, a potom u mreži s kabelskim vodovima. Izvodi niskog napona iz TS SN/NN izvode se u praksi kao zračni (goli vodiči i/ili SKS) i/ili kabelski. Kod zračne mreže niskog napona uzemljivači se izvode kod pojedinih stupova duž trase voda gdje se uzemljuje nul-vodič. U slučaju kabelske mreže uz kabele niskog napona polaže se uzemljivačko uže ili traka (na slici 2 prikazano crtkanom linijom – Cu uže).

2 CALCULATION OF GROUND FAULT CURRENT

A medium-voltage/low-voltage substation is supplied via medium-voltage cable lines and/or aerial lines. Cable lines most often use cables whose metal sheaths are grounded in the corresponding substations. Parallel to each cable is a grounding cable or strip. In this article, for purposes of clarity, an analysis will first be presented of a ground fault in an ungrounded medium-voltage network with aerial lines but without a grounding cable, and then in a network with cable lines. A low-voltage feeder from a medium-voltage/low-voltage substation is in practice an aerial (bare conductors and/or bundled cables and/or cables). In a low-voltage aerial network, the grounding electrodes are installed at some poles along the line where the neutral conductor is grounded. In the case of a cable network, along the low-voltage cable is a grounding cable or grounding strip (shown in Figure 2 by the dotted line – copper cable).



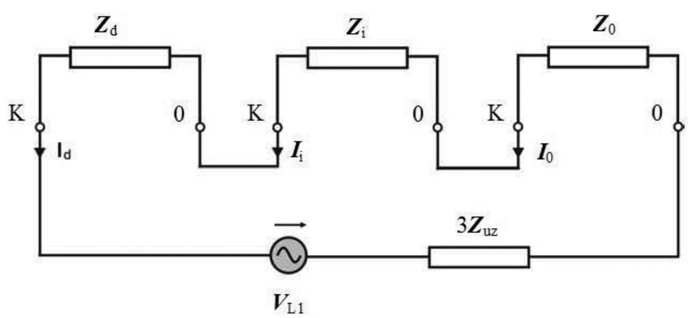
Slika 2 — Zemljospoj na srednjenaponskom nivou u TS SN/NN

Figure 2 — Ground fault at a the medium-voltage level in an MV/LV substation

Pretpostavlja se da je zemljospoj nastao u fazi L1. Kod izračuna struje zemljospoja (I_Z) koristit će se metoda superpozicije. Najprije će se u kratkospojnu vezu (K-D) zanemarivo malog otpora kojom teče struja zemljospoja ubaciti dva fiktivna međusobno suprotno orijentirana naponska izvora. Ovi naponi jednaki su faznom

Let us assume that the ground fault occurred in phase L1. The superposition method will be used in the ground fault current (I_Z) calculation. First of all, in the short-circuit connection, which has negligible low resistance through which the short-circuit current flows, two fictitious voltage sources of mutually opposite polarities are inserted. These voltages naponu koji je vladao na mjestu zemljospoja prije njegovog nastanka (V_{L1}). U skladu s metodom superpozicije može se sustav za vrijeme zemljospoja rastaviti na dva sustava. Jedan od njih je sustav koji je bio prije kvara, a drugi će biti nazvan fiktivnim sustavom. U fiktivnom sustavu egzistira samo fiktivni napon, dok su ostali naponski izvori premošteni, a strujni izvori, ako ih ima, odspojeni. Na osnovi napona na mjestu zemljospoja za vrijeme zemljospoja te struje kroz kratkospojnu vezu (struja zemljospoja) fiktivni sustav može se prikazati u sustavu simetričnih komponenata na način prikazan na slici 3.

are equal to the phase voltage that was present at the ground fault point prior to its occurrence (V_{L1}). According to the superposition method, the system during a ground fault may be divided into two systems. One of them is the system that existed before the fault occurred and the other will be called the fictitious system. In the fictitious system, there is only fictitious voltage, while the other voltage sources are short-circuited, while the current sources, if they exist, are disconnected. On the basis of the voltage at the ground fault point during the ground fault and the current through the short-circuited connection (ground fault current), the fictitious sytem can be presented in a system of symmetrical components as shown in Figure 3.



Slika 3 — Fiktivni sustav u sustavu simetričnih komponenata
Figure 3 — Fictitious system in a system of symmetrical components

Ovdje je:

- Z_d — impedancija sustava gledano s mjesta zemljospoja u direktnom sustavu,
- Z_i — impedancija sustava gledano s mjesta zemljospoja u inverznom sustavu,
- Z_0 — impedancija sustava gledano s mjesta zemljospoja u nultom sustavu,
- Z_{uz} — impedancija između točaka D i 0 (referentna os sustava ili referentna zemlja),
- V_{L1} — fazni napon na mjestu zemljospoja neposredno prije nastanka zemljospoja (obično se uzima da je njegov iznos jednak nazivnoj vrijednosti s kutem 0° prema referentnoj osi).

Stvarne električne veličine (napon i struja) za vrijeme zemljospoja dobiju se superpozicijom vrijednosti u sustavu prije zemljospoja i u fiktivnom sustavu. Budući da prije nastanka zemljospoja nije bilo kratkospojne veze slijedi da je za određivanje struje zemljospoja dovoljan fiktivni sustav.

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Iz slike 3 vidi se da je:

$$\boldsymbol{I}_d = \boldsymbol{I}_i = \boldsymbol{I}_0 = \frac{\boldsymbol{V}_{L1}}{\boldsymbol{Z}_d + \boldsymbol{Z}_i + \boldsymbol{Z}_0 + 3\boldsymbol{Z}_{uz}} \quad . \tag{1}$$

Struja zemljospoja jednaka je:

The ground fault current is equal to:

$$I_z = I_d + I_i + I_0 = 3\,I_0 \,, \tag{2}$$

$$I_z = \frac{3\,V_{L1}}{Z_d + Z_i + Z_0 + 3\,Z_{uz}} \,. \tag{3}$$

Budući da su impedancije uzdužnih grana mnogo manje od impedancija poprečnih grana elemenata sustava može se napisati da je:

Since the impedances of the longitudinal branches are much lower than the impedances of the transversal branches of the system elements, it is possible to write the following:

$$Z_d \ll Z_0 \,, \tag{4}$$

$$Z_i \ll Z_0 \,. \tag{5}$$

Nadalje, uz sljedeće pretpostavke:

Furthermore, under the following assumptions:

$$Z_d \approx 0 + j\,0 \,, \tag{6}$$

$$Z_i \approx 0 + j\,0 \,, \tag{7}$$

$$Z_0 = 0 + \frac{1}{j2\pi f\,C_z} \,, \tag{8}$$

$$Z_{uz} \approx 0 + j\,0 \,, \tag{9}$$

gdje je:

C_z — dozemni kapacitet mreže srednjeg napona u kojoj se desio zemljospoj,
f — frekvencija,

dobije se prema [1] i [2] često korištena relacija za izračun struje zemljospoja koji se dogodio u fazi L3 (pri tom je smjer struje suprotan od onog prikazanog na slici 2):

where

C_z — ground capacitance of the medium-voltage network in which the ground fault occurred,
f — frequency,

according to [1] and [2], a frequently used expression for the calculation of the ground fault current which occurred in Phase L3 is obtained (the direction of the current is opposite to that shown in Figure 2):

$$I_z = \frac{3\,(-V_{L3})}{\dfrac{1}{j2\pi f\,C_z}} \,, \tag{10}$$

$$I_z = \frac{3\,(-\,a\,V_{L1})}{\dfrac{1}{j\,2\pi f\,C_z}} \,, \tag{11}$$

gdje je:

a — operator ($a = e^{j120°}$), pa vrijedi:

where

a — operator ($a = e^{j120°}$), and thus

$$I_z = 3\,V_{L1}\,2\pi f\,C_z\,e^{j30^o} \ . \tag{12}$$

Kod mreže srednjeg napona sa zračnim vodovima bez dozemnog užeta struja mjerodavna za određivanje potencijala nul-vodiča u mreži niskog napona (I_{ZZ}) za vrijeme zemljospoja je:

For a medium-voltage network with aerial cables lines without a grounding cable, the current used for determining the neutral conductor potential in a low-voltage network (I_{ZZ}) during a ground fault is as follows:

$$I_{zz} = I_z \ . \tag{13}$$

Prije je rečeno da mreža srednjeg napona može biti izvedena kabelskim vodovima. U tom slučaju s aspekta uzemljenja metalnih plašteva kabela može se javiti nekoliko slučajeva koji su relevantni za određivanje struje mjerodavne za određivanje potencijala nul-vodiča u mreži niskog napona (I_{ZZ}) za vrijeme zemljospoja. U osnovi postoje dvije grupe kabela i to:

— kabeli koji nemaju metalni plašt,
— kabeli koji imaju metalni plašt.

Pri tom metalni plaštevi kabela mogu biti:

— uzemljeni na oba kraja kabelskog voda,
— uzemljeni na jednom kraju kabelskog voda.

Ako je promatrani kabel uzemljen samo na jednom kraju, tada se razlikuju dva slučaja zemljospoja:

— zemljospoj nastao na mjestu u trafostanici koje je galvanski vezano za metalni plašt kabela i uzemljivački sustav trafostanice ili
— zemljospoj nastao na mjestu koje je galvanski vezano samo za uzemljivački sustav trafostanice (metalni plašt kabela na ovom mjestu nije uzemljen).

Postupak izračuna struje zemljospoja u slučaju kabela bez metalnog plašta i u slučaju kabela s metalnim plaštem kada zemljospoj nastane u TS SN/NN u kojoj nisu metalni plaštevi kabela vezani na uzemljivački sustav trafostanice, dok su na drugom kraju vezani, isti je prije prikazanom. Pri tom je važno napomenuti da u ovom slučaju impedancija Z_{uz} predstavlja ekvivalentnu impedanciju svih vlastitih i međusobnih impedancija elemenata sustava vezanih na uzemljivačke sustave mreža srednjeg i niskog napona (slika 2). Izračunata struja zemljospoja mjerodavna je za

It was previously stated that a medium-voltage network can use cable lines. In this case, from the aspect of the grounded metal cable sheaths, several relevant cases can occur for determining the current for the determination of the neutral-line conductor potential in a low-voltage network (I_{ZZ}) during a ground fault. Basically, there are two groups of cables, as follows:

— cables that do not have a metal sheath,
— cables that have a metal sheath.

Metal cable sheaths can be as follows:

— grounded at both ends of the cable line,
— grounded at one end of the cable line.

If a cable is grounded only at one end, two cases of ground fault can be differentiated:

— the ground fault occurred at a point in a substation which was galvanically connected to the metal cable sheath and the grounding system of the substation, or
— the ground fault occurred at a point that is only galvanically connected to the grounding system of the substation (the metal cable sheath is not grounded at this point).

The procedure for the calculation of the ground fault current in the case of a cable without a metal sheath and in the case of a cable with a metal sheath when a ground fault occurs in an MV/LV substation in which the metal cable sheaths are not connected to the grounding system of the substation, while they are connected at the other end, is the same as previously presented. It is important to note that in this case impedance Z_{uz} represents the equivalent impedance of all the self and mutual impedances of the system elements connected to the grounding systems of the medium-voltage and low-voltage određivanje potencijala nul-vodiča u mreži niskog napona.

U slučaju uzemljenja metalnih plašteva kabela na oba kraja jedan dio struje zemljospoja teći će plaštem, dok će drugi dio teći elementima koji su vezani na uzemljivački sustav i relevantni su za potencijal nul-vodiča [3], [4] i [5].

U slučaju kabelske mreže srednjeg napona utjecaj uzemljivačkih užadi kabela spojenih na uzemljivački sustav promatrane TS SN/NN uzima se u skladu s njihovim elektromagnetskim spregama s ostalim vodičima i pripadnim odvodima [3], [4], [5], [6], [7], [8] i [9].

3 PRORAČUN NAPONA NUL-VODIČA

Promatrajući zemljospoj na slici 2 vidljivo je da će u slučaju nesimetričnog opterećenja duž izvoda niskog napona i zemljospoja na srednjem naponu u pojnoj TS SN/NN teći struje kroz dijelove postrojenja povezane s uzemljivačkim sustavom i pri tom utjecati na napon (potencijal) nul-vodiča. Pod pojmom napona podrazumijeva se napon između neke točke na nul-vodiču i referentne osi (referentne zemlje). Analiza napona nul-vodiča provest će se metodom superpozicije. U skladu s ovom metodom sustav za vrijeme zemljospoja može se rastaviti na dva sustava. Jedan sustav će biti sa sekundarnim namotima transformatora kao naponskim izvorima (ekvivalent s elektromotornim silama i pripadnim impedancijama) i bez struje zemljospoja (stanje prije kvara), a drugi će biti s fiktivnim naponskim izvorom u kratkospojnoj vezi kojim teče struja zemljospoja i premoštenim elektromotornim silama prije spomenutog stvarnog naponskog izvora. Stvarne električne veličine dobiju se zbrajanjem njihovih vrijednosti u jednom i drugom sustavu. Dakle, da bi se odredio utjecaj struje zemljospoja na razini srednjeg napona u pojnoj TS SN/NN na napon nul-vodiča dovoljan je drugi sustav. Najveći napon nul-vodiča bit će u slučaju praznog hoda (neopterećene) mreže niskog napona.

3.1 Teorijske osnove

3.1.1 Zračni izvod niskog napona

Na slici 4 prikazana je TS SN/NN kojoj je na strani niskog napona priključen samo jedan zračni izvod. Postupak je sličan i u slučaju više izvoda niskog napona. Radi pojednostavljenja pretpostavlja se da duž trase voda niskog napona nema priključenih potrošača s pripadnim trošilima, odnosno da je mreža niskog napona u praznom hodu. Nadalje se pretpostavlja da svaki stup zračnog izvoda niskog napona ima

networks (Figure 2). The calculated ground fault current is applicable for the determination of the neutral conductor potential in a low-voltage network.

In the case of metal cable sheaths grounded at both ends, one part of the ground fault current will flow through the sheath while the other part will flow through the elements that are connected to the grounding system and relevant for the neutral conductor potential [3], [4] and [5].

In the case of a medium-voltage cable network, the influence of the grounding cables connected to the grounding system of the MV/LV substation is considered according to their electromagnetic coupling to other conductors and the corresponding output feeders [3], [4], [5], [6], [7], [8] and [9].

3 CALCULATION OF THE NEUTRAL CONDUCTOR VOLTAGE

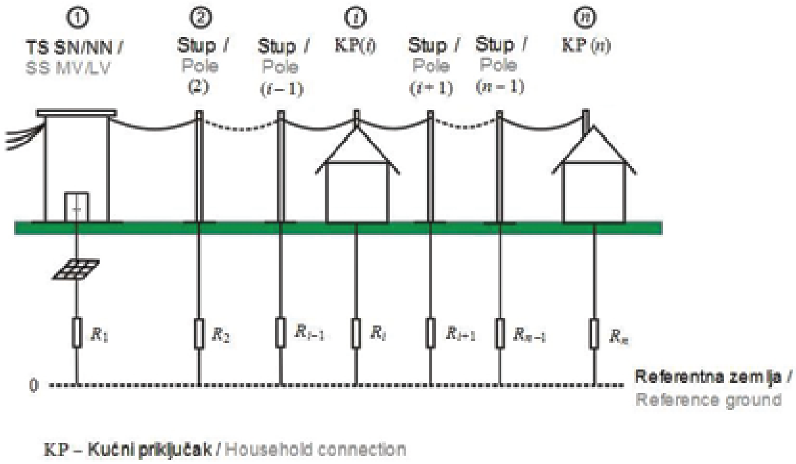
From the ground fault in Figure 2, it is evident that in the case of an asymmetrical load along the low-voltage feeder and ground fault at medium-voltage in an MV/LV supply substation, current will flow through the parts of the equipment connected to the grounding system and thus influence the voltage (potential) of the neutral conductor. The term voltage is understood to mean the voltage between a point on the neutral conductor and the reference axis (reference ground). Analysis of the neutral conductor voltage will be performed by the superposition method. According to this method, the system during a ground fault can be divided into two systems. One system will have secondary windings of the transformer as voltage sources (equivalent to electromotive forces and the corresponding impedances) and without ground fault current (the state prior to the fault), and the other will have a fictitious voltage source in a short-circuit connection through which ground fault current flows and short-circuited electromotive forces of the previously mentioned actual voltage source. The actual electrical values are obtained as the sum of the values in both systems. Therefore, the second system is sufficient in order to determine the influence of the ground fault current at the medium-voltage level in a supply MV/LV substation upon the neutral conductor voltage. The highest neutral conductor voltage will occur in the case of the no-load operation of a low-voltage network.

3.1 Theoretical foundations

3.1.1 Load voltage aerial feeder

In Figure 4, an MV/LV substation is presented to which only one aerial feeder is connected at the low-voltage level. The procedure is similar in the case of several low-voltage feeders. In order to simplify presentation, let it be assumed that there are no customers with their corresponding loads connected along the low-svoj uzemljivač karakteriziran pripadnim otporom. Cilj proračuna je odrediti napon nul-vodiča duž trase izvoda niskog napona za vrijeme zemljospoja na razini srednjeg napona u pripadnoj TS SN/NN.

voltage line, i.e. the low-voltage network is in no-load operation. Furthermore, it is assumed that each pole of the low-voltage aerial feeder has its own grounding electrode and the corresponding grounding resistance. The goal of the calculation is to determine the neutral conductor voltage along the low-voltage feeder during a ground fault at the medium-voltage level in the corresponding MV/LV substation.



Slika 4 — Zračni izvod niskog napona iz TS SN/NN
Figure 4 — Low-voltage aerial feeder from an MV/LV

gdje je:

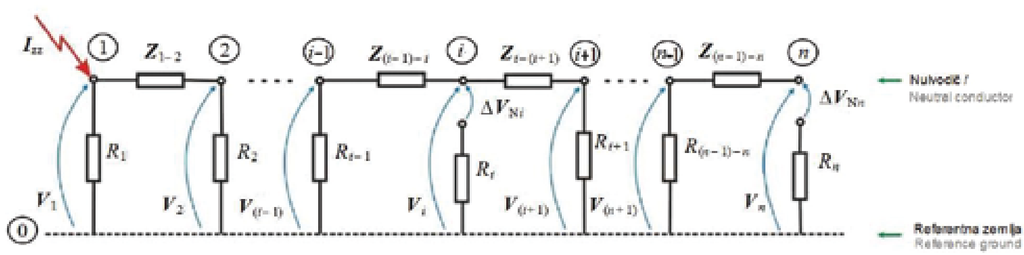
R_1 — otpor uzemljivača TS SN/NN,
R_2,..., R_{i-1} ,..., R_{i+1},..., R_{n-1} — otpor uzemljivača stupa,
R_i, R_n — otpor uzemljivača potrošača.

Na slici 5 prikazana je ekvivalentna shema ovakvog sustava u slučaju zemljospoja na razini srednjeg napona u promatranoj TS SN/NN. Budući da se analizira slučaj praznog hoda mreže niskog napona (neopterećena mreža), promatra se samo nul-vodič s pripadnim uzemljivačima trafostanice, stupova i kućnih priključaka (KP).

where

R_1 — grounding resistance of an MV/LV substation,
R_2,..., R_{i-1} ,..., R_{i+1},..., R_{n-1} — pole grounding resistance, and
R_i, R_n — grounding resistance of a customer facility.

In Figure 5, an equivalent diagram is presented of such a system in the event of a ground fault at the medium-voltage level in an MV/LV substation. Since no-load operation of the low-voltage network is analyzed, only the neutral conductor with the corresponding grounding electrodes of the substation, poles and household connections are considered.



Slika 5 — Ekvivalentna shema zračnog izvoda niskog napona u slučaju zemljospoja u TS SN/NN
Figure 5 — Equivalent diagram of a low-voltage aerial feeder in the event of a ground fault in an MV/LV substation

Prema Carsonu [1], [10] i [11] uzdužna impedancija Z_{i-j} jednaka je:

According to Carson [1], [10] and [11], longitudinal impedance Z_{i-j} equals:

$$\boldsymbol{Z}_{\mathrm{v}1} = R_{\mathrm{v}1} + \frac{\omega\,\mu_0}{8} + \mathrm{j}\,\frac{\omega\,\mu_0}{2\,\pi}\,\ln\left(\frac{658}{r'}\sqrt{\frac{\rho}{f}}\right), \tag{14}$$

$$\boldsymbol{Z}_{i-j} = \boldsymbol{Z}_{\mathrm{v}1}\cdot l_{i-j}\ . \tag{15}$$

Oznake su :

- $R_{\mathrm{v}1}$ — radni otpor nul-vodiča po jedinici duljine,
- $Z_{\mathrm{v}1}$ — uzdužna impedancija nul-vodiča po jedinici duljine,
- $l_{i\text{-}j}$ — duljina dionice *i-j* nul-vodiča,
- ω — kružna frekvencija, $\omega = 2\pi f$,
- f — frekvencija,
- μ_0 — magnetska permeabilnost vakuma,
- ρ — specifični električni otpor (električna otpornost) tla,
- r' — reducirani polumjer vodiča (nul-vodiča),
- R_i — otpor i-tog uzemljivača (izmjeren ili izračunat).

where

- $R_{\mathrm{v}1}$ — the active resistance of the neutral conductor per unit of length,
- $Z_{\mathrm{v}1}$ — the longitudinal impedance of the neutral conductor per unit of length,
- $l_{i\text{-}j}$ — section length *i-j* of the neutral conductor,
- ω — angular frequency, $\omega = 2\pi f$,
- f — frequency,
- μ_0 — magnetic permeability of vacuum,
- ρ — specific soil resistivity,
- r' — reduced conductor radius (neutral conductor),
- R_i — i-th grounding resistance (measured or calculated).

Za mrežu sa slike 5 može se napisati sljedeća matrična jednadžba za određivanje napona nul-vodiča.

For the network from Figure 5, it is possible to write the following matrix equation for the determination of the neutral conductor voltage:

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2i} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{i1} & Y_{i2} & \cdots & Y_{ii} & \cdots & Y_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} I_{\mathrm{zz}} \\ 0 \\ \vdots \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \tag{16}$$

gdje je:

- Y_{ii} — vlastita admitancija *i*-tog čvora, $i = 1, 2, \ldots, n$
- Y_{ij} — međusobna admitancija *i*-tog i *j*-tog čvora, $i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, n;\ i \neq j$.

where

- Y_{ii} — self admittance of the i-th note, $i = 1, 2, \ldots, n$
- Y_{ij} — mutual admittance of the *i*-th and *j*-th nodes, $i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, n;\ i \neq j$..

Napon *i*-tog mjesta na nul-vodiču jednak je:

The voltage of the i-th point on the neutral conductor equals:

$$\boldsymbol{V}_{\mathrm{N}i} = \boldsymbol{V}_i\ , \qquad i = 1, 2, \ldots, n. \tag{17}$$

Napon između nul-vodiča i vlastitog uzemljivača u objektu i-tog potrošača (slika 5) jednak je:

The voltage between the neutral conductor and the grounding electrode of the facility of the i-th customer (Figure 5) equals:

$$\Delta \boldsymbol{V}_{\mathrm{N}i} = \boldsymbol{V}_{\mathrm{N}i} \ . \tag{18}$$

3.1.2 Kabelski izvod niskog napona

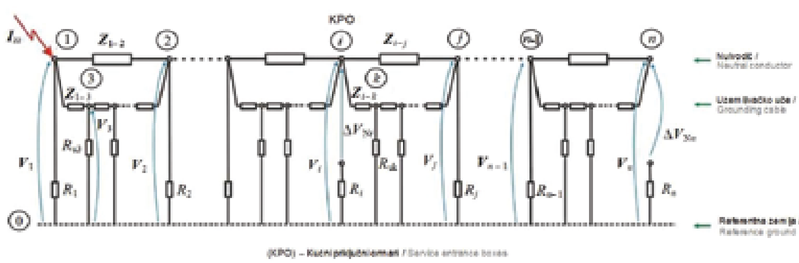
Na slici 6 prikazana je TS SN/NN kojoj je na strani niskog napona priključen samo jedan kabelski izvod. Sličan postupak je i u slučaju više izvoda. Radi pojednostavljenja, kao i kod zračnog izvoda pretpostavljeno je da duž trase voda niskog napona nema priključenih potrošača s pripadnim trošilima, odnosno da je mreža niskog napona u praznom hodu.

Nadalje se pretpostavlja da svaki kabelski ormarić na kabelskom izvodu niskog napona ima svoj uzemljivač karakteriziran pripadnim otporom. Na slici 6 prikazana je ekvivalentna shema sustava za izračun napona nul-vodiča u slučaju zemljospoja na razini srednjeg napona u promatranoj TS SN/NN. Budući da se analizira slučaj praznog hoda mreže niskog napona (neopterećena mreža), promatra se samo nul-vodič, uzemljivačka užad ili trake, uzemljivači kabelskih razvodnih ormara (KRO) i uzemljivači potrošača (kućni priključni ormari (KPO)).

3.1.2 Low-voltage cable feeder

In Figure 6, an MV/LV substation is presented to which only one cable feeder is connected on the low-voltage side. The procedure is similar in the case of several feeders. For the purpose of simplification, as with the aerial feeder, it is assumed that there are no customers with their corresponding loads connected along the low-voltage line, i.e. the low-voltage network is under no-load operation.

Furthermore, it is assumed that every cable box on the low-voltage cable feeder has its own grounding electrode characterized by the corresponding resistance. In Figure 6, an equivalent system diagram is presented for the calculation of neutral conductor voltage in the case of a ground fault at the medium-voltage level in an MV/LV substation. Since the no-load operation of a low-voltage network is analyzed, only the neutral conductor, grounding cables or strips, the grounding electrodes of the cable distribution boxes and the grounding electrodes of the customer facilities (service entrance boxes) are taken into account.



Slika 6 — Ekvivalentna shema kabelskog izvoda niskog napona u slučaju zemljospoja u TS SN/NN

Figure 6 — Equivalent diagram of a low-voltage cable feeder in the case of a ground fault in an MV/LV substation

Uzdužne impedancije grana računaju se prema izrazima (14) i (15). Pri tom je $l_{i\text{-}j}$ u slučaju nul-vodiča duljina dionice, dok je u slučaju uzemljivačkog užeta duljina $i\Delta$-tog segmenta Δl_{ui}. Budući da je uzemljivačko uže unutar dionice prikazano pomoću lanca T shema, za početnu i krajnju uzdužnu impedanciju unutar dionice uzima se duljina $\frac{\Delta l_{ui}}{2}$.

Otpor poprečne grane i-tog segmenta uzemljivačkog užeta duljine Δl_{ui} može se izračunti pomoću sljedećeg izraza [11]:

Longitudinal branch impedance values are calculated according to expressions (14) and (15). The section length of the neutral conductor is $l_{i\text{-}j}$ while in the case of the grounding cable the length of the i-th segment is Δl_{ui}. Since the grounding cable within the section is presented using a series of T circuits, for the first and last longitudinal impedance within a section, the length $\frac{\Delta l_{ui}}{2}$ is taken.

The resistance of the transversal branch of the i-th segment of the grounding cable of the length Δl_{ui} can be calculated using the following expression [11]:

$$R_{ui} = \frac{\rho}{\pi\,\Delta l_{ui}} \ln \frac{\Delta l_{ui}}{\sqrt{2\,H\,r_{ui}}} \quad , \tag{19}$$

gdje je:

H — dubina ukopavanja uzemljivačkog užeta,
r_{ui}— polumjer uzemljivačkog užeta.

Na slici 6 otpor uzemljivača TS SN/NN označen je R_1, dok su otpori uzemljivača potrošača označeni R_i i R_n . Otpor uzemljivača KRO, ako postoji, označen je R_j, $j = 2, \ldots, (n-1), j \neq i$.

Nakon formiranja matrice vlastitih i međusobnih admitancija čvorova mreže prikazane na slici 6 može se odrediti napon nul-vodiča koristeći se izrazom (16).

Napon i-tog mjesta na nul-vodiču jednak je:

where

H — burial depth of the grounding cable,
r_{ui}—radius of the grounding cable.

In Figure 6, the grounding resistance of the MV/LV substation is R_1, while the grounding resistances of the customer facilities are R_i and R_n . The grounding resistance of the cable distribution box, if it exists, is R_j, $j = 2, \ldots, (n-1), j \neq i$.

After the formation of the matrix of self and mutual node admittances of the network shown in Figure 6, it is possible to determine the neutral conductor voltage using Expression (16).

The voltage of the i-th point on the neutral conductor equals:

$$\boldsymbol{V}_{Ni} = \boldsymbol{V}_i \,, \quad i = 1, 2, \ldots, n. \tag{20}$$

Napon između nul-vodiča i vlastitog uzemljivača u objektu i-tog potrošača (slika 6) jednak je:

The voltage between the neutral conductor and the grounding electrode in the facility of the i-th customer (Figure 6) equals:

$$\Delta \boldsymbol{V}_{Ni} = \boldsymbol{V}_{Ni} \;. \tag{21}$$

4 NAPON NUL-VODIČA U REALNOJ MREŽI NISKOG NAPONA

Za primjer su odabrana dva segmenta distribucijske mreže DP Elektrodalmacija Split (TS 10(20)/0,4 kV Bračevići 4 i TS 10(20)/0,4 kV Krč) kod kojih su mreže 10(20) kV u pogonu s izoliranim zvjezdištima. Prva se napaja iz TS 35/10(20) kV Muć, a druga iz TS 35/10(20) kV Klis. Za obje je zajedničko da se njihove mreže 10 kV i 0,4 kV rasprostiru kraškim terenom s vrlo visokim specifičnim električnim otporom tla. TS 35/10(20) kV Muć instalirane snage 2 x 4 MVA ruralna je trafostanica koja pokriva široko područje bez većih gospodarskih aktivnosti. Trenutačno je u pogonu samo jedan transformator, dok je drugi u rezervi. Mreža 10(20) kV napajana iz ove trafostanice pretežno

4 NEUTRAL CONDUCTOR VOLTAGE IN AN ACTUAL LOW-VOLTAGE NETWORK

As an example, two segments of the distribution network DP Elektrodalmacija Split (the Bračevići 4 10(20)/0,4 kV substation and the Krč 10(20)/0,4 kV substation), for which the 10(20) kV networks are in operation with isolated neutral points, have been selected. The first is supplied from the Muć 35/10(20) kV substation and the second from the Klis 35/10(20) kV substation. Both their 10 kV and 0,4 kV networks extend into karstic terrain with high specific soil resistivity. The Muć 35/10(20) kV substation has an installed capacity of 2 x 4 MVA and is a rural substation that covers a broad area without major economic activity. Currently, only one transformer is in operation while the second is in reserve. The 10(20) kV network supplied from this substation is primarily aerial. The area je zračna. Područje napajano iz TS 35/10(20) kV Klis, instalirane snage 2 x 8 MVA, specifično je po iznimno brzom prirastu novih potrošača, u prvom redu zbog naglog širenja poduzetničke zone Podi, te zbog izgradnje auto-ceste Zagreb – Šestanovac. Mreža naponske razine 10(20) kV napajana iz ove trafostanice mješovitog je kabelsko-zračnog karaktera. Naime, svi novi izvodi su u pravilu kabelski, dok su stari izvodi zračni. Nagli razvoj ove mreže ima za posljedicu naglo povećanje struje zemljospoja. Razlog za odabir ove konkretne mreže je, pored ostalog i njena konfiguracija. U zoni Podi svi izvodi 10(20) kV i 0,4 kV izvedeni su isključivo kabelski. Okolna sela napajaju se zračnim vodovima 10(20) kV. Pored toga, izvodi 0,4 kV u ovim selima su isključivo zračni, izvedeni golim vodičima i samonosivim kabelskim snopom.

4.1 Struja zemljospoja

U ovom primjeru analizira se zemljospoj na naponskoj razini 10 kV u TS 10(20)/0,4 kV Bračevići 4, odnosno u TS 10(20)/0,4 kV Krč.

TS 10(20)/0,4 kV Bračevići 4

TS 10(20)/0,4 kV Bračevići 4 instalirane snage 250 kVA stupna je trafostanica (u daljnjem tekstu: STS) napajana zračnim vodom 10(20) kV iz TS 35/10(20) kV Muć, a njena mreža 0,4 kV sastoji se od tri SKS izvoda na drvenim i betonskim stupovima. Iznos struje zemljospoja na naponskoj razini 10 kV stupne trafostanice izračunat na modelu u skladu s jednadžbom (3) iznosi:

supplied from the Klis 35/10(20) kV substation has an installed capacity of 2 x 8 MVA and is characterized by an exceptionally rapid increase in the number of new customers, primarily due to the sudden expansion of the Podi entrepreneurial zone and the construction of the Zagreb – Šestanovac Highway. The 10(20) kV network supplied from this substation is of a mixed cable-aerial character. All the new feeders are as a rule cable, while the old feeders are aerial. The sudden development of this network has resulted in a sudden increase in the ground fault current. A reason for the selection of this specific network, among others, is its configuration. In the Podi zone, all the 10(20) kV and 0,4 kV feeders are cable feeders. The surrounding villages are supplied by 10(20) kV aerial lines. Moreover, the 0,4 kV feeders in these villages are all aerial, with bare conductors and bundled cables.

4.1 Ground fault current

In this example, a ground fault is analyzed at a voltage level of 10 kV at the Bračevići 4 10(20)/0,4 kV substation and the Krč 10(20)/0,4 kV substation.

Bračevići 4 10(20)/0,4 kV substation

The Bračevići 4 10(20)/0,4 kV substation, with an installed capacity of 250 kVA, is a pole substation supplied by a 10(20) kV aerial line from the Muć 35/10(20) kV substation. Its 0,4 kV network consists of three bundled cable feeders on wooden and concrete poles. The value of the ground fault current at the 10 kV voltage level of the pole substation calculated on the model according to Equation (3) is

$$I_z = 4{,}46\,\mathrm{A}\ . \tag{23}$$

U tablici 1 prikazani su iznosi struja zemljospoja (I_z) dobiveni mjerenjem u vlažnom (19.5.2006. godine) i suhom razdoblju (4.7.2006. godine).

In Table 1, the ground fault currents (I_z) obtained by measurement in a rainy period (2006-05-19) and a dry period (2006-07-04) arre presented.

Tablica 1– Izmjereni iznos struje zemljospoja
Table 1– Measured ground fault current values

Redni broj / Ordinal Number	Mjesto zemljospoja (Mjerno mjesto) / Grount fault point (measurement site)	Konfiguracija mreže / Network configuration	Datum mjerenja / Date of measurement	
			2006-05-19	2006-07-04
			I_z [A]	I_z [A]
1	TS / SS 35/10(20) kV Muć (10 kV)	Cijela 10(20) kV mreža u pogonu / Entire 10(20) kV network in operation	4,2	4,1
2	STS / PSS 10(20)/0,4 kV Bračevići 4, (10 kV)	Spojeni uzemljivači cjelokupne mreže niskog napona priključene na STS / The grounding electrodes of the entire low-voltage network connected to the pole substation are bonded together.	3,53	3,4
3	STS / PSS 10(20)/0,4 kV Bračevići 4, (10 kV)	Odspojeni uzemljivači cjelokupne mreže niskog napona, priključen samo uzemljivač STS / The grounding electrodes of the entire low-voltage network are disconnected, and only the grounding electrode at the pole substation is connected.	3,3	3,2

Uspoređujući vrijednosti dobivene na modelu s mjerenjem uočavaju se neke razlike koje su rezultat nemogućnosti točnog izračunavanja dozemnih kapaciteta relevantnih elemenata mreže i nepoznavanja otpora dijela električnog kruga kojim teče struja zemljospoja.

TS 10(20)/0,4 kV Krč

TS 10(20)/0,4 kV Krč instalirane snage 630 kVA napaja se kabelskim vodom 10(20) kV iz TS 35/10(20) kV Klis. Kabelski vod izveden je s tri kabela 20 kV, tipa XHE 49-A, 1x150 mm^2, položenih u trolist. Iznos struje zemljospoja na naponskoj razini 10 kV trafostanice TS 10(20)/0,4 kV Krč izračunat na modelu u skladu s jednadžbom (3) iznosi:

Comparing the values obtained on the model with the measured values, several differences are noted resulting from the impossibility of the precise calculation of the ground capacitances of the relevant network elements and the unknown resistance of the part of the electrical circuit through which the ground fault current flows.

Krč 10(20)/0,4 kV substation

The Krč 10(20)/0,4 kV substation, 630 kVA installed capacity, is supplied by a 10(20) kV cable line from the Klis 35/10(20) kV substation. The calbe line has three 20 kV cables, Type XHE 49-A, 1x150 mm^2, in trefoil formation. The ground fault current value at the 10 kV voltage level of the Krč 10(20)/0,4 kV substation calculated using the model according to Equation (3) is:

$$I_z = 87{,}58 \text{ A} . \qquad (24)$$

Izmjerena vrijednost ove struje dana je u tablici 2 za suhi (2006-09-07) i vlažni (2006-09-26) kraški teren.

The measured value of this current is given in Table 2 for dry (2006-09-07) and wet (2006-09-26) karstic terrain.

Tablica 2 – Izmjereni iznos struje zemljospoja
Table 2 – Measured ground fault current values

Datum mjerenja / Date of measurement	I_z [A]
2006-09-07	88,6
2006-09-26	87,5

4.2 Napon nul-vodiča zračnog izvoda niskog napona

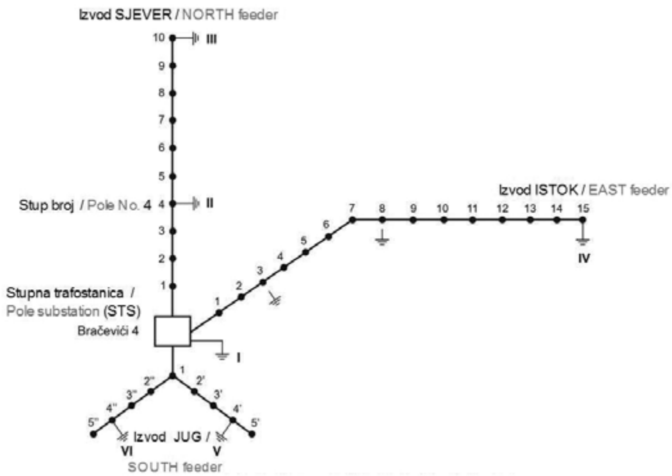
Odabrana je mreža niskog napona napajana iz STS 10(20)/0,4 kV Bračevići 4 iz razloga što je topološki jednostavna i napaja mali broj potrošača. STS 10(20)/0,4 kV Bračevići 4 je stupna trafostanica izgrađena tijekom devedesetih godina prošlog stoljeća. Napaja se zračnim vodom 10(20) kV iz TS 35/10(20) kV Muć, a njena mreža 0,4 kV sastoji se od tri zračna SKS izvoda na drvenim i betonskim stupovima kojima se mali zaseoci napajaju električnom energijom.

Budući da se analizirana distribucijska mreža nalazi na kraškom terenu, gdje specifični električni otpor zemlje znatno ovisi o vremenskim prilikama (padalinama), mjerenje otpora uzemljivača vršeno je u vlažnom (2006-05-19) i suhom razdoblju (2006-07-04). Na slici 7 prikazana je analizirana mreža niskog napona napajana iz STS 10(20)/0,4 kV Bračevići 4.

4.2 Neutral conductor voltage of a low-voltage aerial feeder

The low-voltage supply network from the Bračevići 4 10(20)/0,4 kV pole substation was selected because it is topologically simple and supplies a small number of customers. The Bračevići 4 10(20)/0,4 kV pole substation was built during the 1990s. It is supplied by a 10(20) kV aerial line from the Muć 10(20) kV substation. Its 0,4 kV network consists of three aerial feeders (bundled cables) on wood and concrete poles, via which small villages are supplied with electricity.

Since the distribution network analyzed is located on karstic terrain, where the specific soil resistivity significantly depends upon the weather (precipitation), grounding resistance was measured during a wet period (2006-05-19) and a dry period (2006-07-04). In Figure 7, the analyzed low-voltage network supplied by the Bračevići 4 10(20)/0,4 kV pole substation is presented.



Slika 7 — Mreža niskog napona napajana iz stupne TS 10(20)/0,4 kV Bračevići 4
Figure 7 — Low-voltage network supplied from the Bračevići 4 10(20)/0,4 kV pole substation

Prije početka mjerenja na realnoj mreži napravljene su opsežne pripreme. Snimljena je cijela mreža niskog napona i izvršena su premjeravanja svih relevantnih udaljenosti u mreži. Izvršena su mjerenja otpora svih uzemljivača koji se nalaze u navedenoj mreži (**I**, **II**, **III**, **IV**, **V** i **VI**), osim uzemljivača potrošača.

Otpor uzemljivača stupne TS 10(20)/0,4 kV Bračevići 4 (RU STS) za različite datume mjerenja prikazan je u tablici 3.

Extensive preparations were conducted prior to the beginning of the measurement of the actual network. Data on the entire low-voltage network were taken and measurements were performed of all the relevant distances in the network. Ground resistance measurements of all the grounding electrodes in the network (**I**, **II**, **III**, **IV**, **V** and **VI**) were performed, except for the customer grounding electrodes.

Grounding resistance of the Bračevići 4 10(20)/0,4 kV pole substation (RG PS) for various dates of measurement is shown in Table 3.

Tablica 3 – Izmjereni otpor uzemljivača STS
Table 3 – Measured grounding resistance of the pole substation

Oznaka / Designation	Uzemljivač I / Grounding electrode 1	
Datum mjerenja / Date of measurement	2006-05-19	2006-07-04
$R_{U\ STS}$ [Ω] / $R_{G\ PS}$	30,5	71,5

Bitno je napomenuti da su tijekom mjerenja otpora uzemljivača stupne trafostanice nulvodiči sva tri izvoda niskog napona odspojeni u stupnoj trafostanici kako bi se eliminirao utjecaj uzemljivača izvedenih duž trase voda niskog napona. Pored ovih podataka, izmjerene su relevantne udaljenosti po izvodima, također i otpor uzemljivača stupova duž trase voda niskog napona ($R_{U\ stupa}$). U tablici 4 prikazani su podaci za prvi izvod niskog napona (izvod SJEVER). Duljina raspona odnosi se na raspon koji prethodi dotičnom stupu, tako da je za prvi stup duljina raspona udaljenost od STS do prvog stupa. Također se vidi kod kojih stupova je nulvodič uzemljen (stupovi br. 4 i 10), a kod kojih nije (stupovi kod kojih nema upisanog podatka

It is important to note that during the measurement of the grounding resistance of the pole substation, the neutral conductors of all three low-voltage feeders were disconnected in the pole substation in order to eliminate the influence of the grounding electrodes installed along the low-voltage line. In addition to these data, the relevant distances for each feeder were measured, as well as the grounding resistance of the poles along the low-voltage line ($R_{G\ pole}$). In Table 4, data are presented for the first low-voltage feeder (NORTH feeder). The spacing length refers to the distance between a pole and the preceding pole, or in the case of the first pole the distance from the pole substation. It is also evident at which poles the neutral conductor is grounded (poles No. 4 and 10), and at which they are not (the poles for which there is no o otporu uzemljenja). U tablici 4 prikazani su izmjereni podaci za izvod niskog napona SJEVER.

data entered on the grounding resistance). In Table 4, measured data are presented for the low-voltage NORTH feeder.

Tablica 4 – Izvod niskog napona SJEVER
Table 4 – Low-voltage NORTH feeder

Broj stupa / Pole No.			1	2	3	4	5	6	7	8	9	10
Oznaka uzemljivača / Designation of grounding electrode						II						III
Duljina raspona / Spacing length			35	36	33	34	38	34	37	35	36	39
Datum mjerenja / Date of measurement	2006-05-19	RU stupa / RG pole [Ω]				63						34
	2006-07-04					170						50

U tablici 5 prikazani su izmjereni podaci za drugi izvod niskog napona (izvod ISTOK). Ovaj izvod napaja samo jednu kuću na kraju izvoda i izvod niskog napona izveden je na način da je SKS vod postavljen na stupove DV 10(20) kV. Stupovi br. 3, 8 i 15 su betonski s izvedenim uzemljivačima. Nul-vodič mreže niskog napona uzemljen je samo kod potrošača, tj. na stupnom mjestu br. 15. Otpori uzemljivača stupova koji nisu spojeni s nul-vodičem (stupovi br. 3 i 8) su podcrtani u tablici 5.

In Table 5, the measured data are presented from the second low-voltage feeder (EAST feeder). This feeder supplies only one house at the end of the feeder and the low-voltage feeder is installed in such a manner that the bundled cable line is supported by poles of the 10(20) kV distribution line. Poles No. 3, 8 and 15 are concrete and installed with grounding electrodes. The neutral conductor of the low-voltage network is grounded only in the customer's installation, i.e. at pole site No. 15. The grounding resistances of the poles that are not connected to the neutral conductor (Poles No. 3 and 8) are underlined in Table 5.

Tablica 5 – Izvod niskog napona ISTOK
Table 5 – Low-voltage EAST feeder

Broj stupa / Pole No.			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Oznaka uzemljivača / Designation of grounding electrode																	IV
Duljina raspona / Spacing length [m]			42	39	41	38	40	32	46	29	41	39	40	38	38	40	38
Datum mjerenja / Date of measure-ment	2006-05-19	RU stupa / RG pole [Ω]			21					22							21
	2006-07-04						39		46			50					46

Izmjereni podaci za treći izvod prikazani su u tablici 6. Iz navedenih podataka vidi se da kod prvog stupa taj izvod dijeli na dva podizvoda koji napajaju dvije grupe potrošača.

The data measured for the third feeder are presented in Table 6. From these data, it is evident that for the first pole the feeder is divided into two subfeeders which supply two groups of customers.

Tablica 6 – Izvod niskog napona JUG
Table 6 – Low-voltage SOUTH feeder

Broj stupa / Pole No.			1	2'	3'	4'	5'	2''	3''	4''	5''
Oznaka uzemljivača / Designation of grounding electrode						V				VI	
Duljina raspona / Spacing length [m]			30	22	30	25	10	25	10	16	25
Datum mjerenja / Date of measurement [Ω]	2006-05-19	RU stupa / RG pole				16				20	
	2006-07-04					23				49	

Analizirajući prethodne tablice uočava se da se vrijednosti otpora uzemljivača znatno razlikuju

When analyzing the previous tables, it is evident that the values of the grounding resistance differ signifii da ovise o meteorološkim prilikama (vlažano ili suho razdoblje). S aspekta napona nul-vodiča nepovoljnija je situacija kada su otpori uzemljivača viši.

U skladu s tim, kod proračuna napona čvorišnih točaka na nul-vodiču stvarne mreže niskog napona priključene na stupnu TS 10(20)/0,4 kV Bračevići 4 uzeti su podaci od 2006-07-04. Analiza je provedena za sljedeće slučajeve:

— svi uzemljivači od **I** do **VI** su spojeni na nul-vodič,
— odspojen uzemljivač **II**,
— odspojen uzemljivač **III**,
— odspojeni uzemljivači **II** i **III**,
— odspojeni uzemljivači **II**, **III** i **VI**,
— odspojen uzemljivač **VI**,
— spojen samo uzemljivač STS (**I**), ostali odspojeni.

Izračunati iznosi napona nul-vodiča na mjestima **I**, **II**, **III**, **IV**, **V** i **VI** dani su u tablici 7.

cantly and that they depend upon the meteorological conditions (wet or dry period). From the aspect of the neutral conductor voltage, the situation is unfavorable when the grounding resistance is higher.

Therefore, in the calculation of the voltage of the node points on the neutral conductor of the actual low-voltage network connected to the Bračevići 4 10(20)/0,4 kV pole substation, data from 2006-07-04 are used. Analysis was performed for the following cases:

— all grounding electrodes from **I** to **VI** are connected to the neutral conductor,
— disconnected grounding electrode **II**,
— disconnected grounding electrode **III**,
— disconnected grounding electrodes **II** and **III**,
— disconnected grounding electrodes **II**, **III** and **VI**,
— disconnected grounding electrode **VI**,
— only the grounding electrode of the pole substation (**I**) is connected, the others are disconnected.

The calculated values for the neutral conductor voltage at points **I**, **II**, **III**, **IV**, **V** and VI are presented in Table 7.

Tablica 3 – Izmjereni otpor uzemljivača STS
Table 3 – Measured grounding resistance of the pole substation

Stanje mreže niskog napona / State of the low-voltage network	I_Z [A]	V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]	V_V [V]	V_{VI} [V]
Spojeni svi uzemljivači mreže niskog napona / All grounding electrodes of the low-voltage network are connected	4,46	35,58	35,51	35,43	35,55	35,48	35,52
Odspojen uzemljivač II / Grounding electrode II is disconnected	4,46	37,32	37,28	37,19	37,29	37,22	37,27
Odspojen uzemljivač III / Grounding electrode III is disconnected	4,46	42,29	42,27	42,27	42,28	42,17	42,22
Odspojeni uzemljivači II i III / Grounding electrodes II and III are disconnected	4,46	44,75	44,75	44,75	44,75	44,63	44,69
Odspojeni uzemljivači II, III i VI / Grounding electrodes II, III and VI are disconnected	4,46	56,29	56,29	56,29	56,29	56,15	56,25
Odspojen uzemljivač VI / Grounding electrode VI is disconnected	4,46	42,48	42,40	42,30	42,47	42,37	42,44
Spojen samo uzemljivač STS (oznaka I), ostali uzemljivači II, III, IV, V i VI odspojeni / Only the grounding electrode of the pole substation (Designation I) is connected. The other grounding electrodes II, III, IV V and VI are disconnected.	4,46	311,2	311,2	311,2	311,2	311,2	311,2

Zbog minimiziranja troškova mjerenja, vodeći računa pri tom da se izmjerene vrijednosti mogu usporediti s izračunatim, mjerenje prije analiziranih napona nul-vodiča izvršeno je jednim instrumentom MI 2292 METREL koji ima šest kanala, tri za mjerenje struje i tri za mjerenje napona. U ovom slučaju korištena su tri ka-

In order to minimize measuring costs, taking into account that the measured values can be compared with the calculated values, measurement of the previously analyzed neutral conductor voltages was performed using an MI 2292 METREL instrument, which has six channels, three for measuring current and three for measuring voltage. In this case, the three nala za mjerenje napona na prije spomenutim mjestima, a jedan kanal za mjerenje struje zemljospoja. Rezultati ovih mjerenja dani su u tablici 8.

channels for measuring voltage were used at the aforementioned points, and one channel was used for measuring ground fault current. The results of these measurements are presented in Table 8.

Tablica 8 – Izmjereni iznosi napona nul-vodiča i struje zemljospoja u mreži niskog napona
Table 8 – Measured neutral conductor voltage and ground fault current values in the low-voltage network

Stanje mreže niskog napona / State of the low-voltage network	I_Z [A]	V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]	V_V [V]	V_{VI} [V]
Spojeni svi uzemljivači mreže niskog napona / All the grounding electrodes of the low-voltage network are connected	3,4	25,1	25,0	24,9			25,0
Odspojen uzemljivač II / Grounding electrode II is disconnected	3,4	25,8		25,6			25,7
Odspojen uzemljivač III / Grounding electrode III is disconnected	3,4	26,5	26,4				26,3
Odspojeni uzemljivači II i III / Grounding electrodes II and III are disconnected	3,3	26,5					26,3
Odspojeni uzemljivači II, III i VI / Grounding electrodes II, III and VI are disconnected	3,3	28,4					
Odspojen uzemljivač VI / Grounding electrode VI is disconnected	3,3	26,2	26,1	26,1			
Spojen samo uzemljivač STS (oznaka I), ostali uzemljivači II, III, IV, V i VI odspojeni / Only the grounding electrode of the pole substation (Designation I) is connected. The other grounding electrodes II, III, IV V and VI are disconnected.	3,2	221,6					

Najveća izračunata vrijednost napona na modelu je 311,2 V, a najveća izmjerena vrijednost u realnoj mreži je 221,6 V i javlja se u slučaju kada su svi uzemljivači duž nul-vodiča bili odspojeni. Razlika se javlja zbog, kako je prije rečeno, nemogućnosti definiranja egzaktnog modela, tj. točnog izračunavanja dozemnih kapaciteta relevantnih elemenata mreže i nepoznavanja otpora dijela električnog kruga kojim teče struja zemljospoja. Ovaj iznos napona, koji u najgorem slučaju može biti napon dodira na nekom mjestu u mreži (ΔV_{Ni}), može biti opasan po život i zaštita od zemljospoja mora biti podešena tako da se eliminira ova opasnost. Iz svih predočenih rezultata zaključuje se da je sa stanovišta sigurnosti povoljnije da je nul-vodič uzemljen na što je god moguće više mjesta, naročito ako se radi o kraškom terenu.

4.3 Napon nul-vodiča kabelskog voda niskog napona

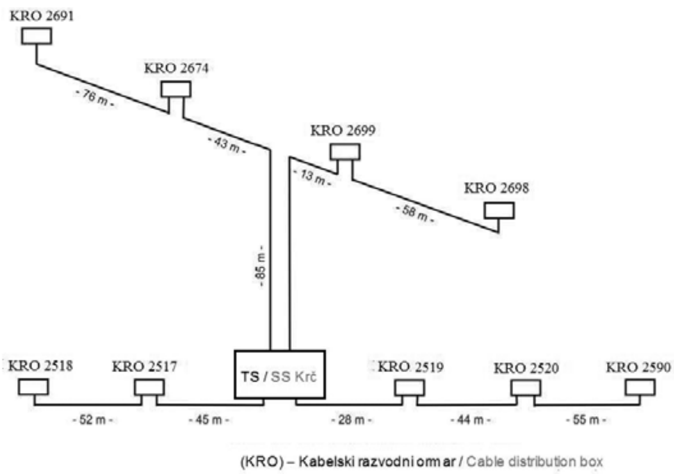
Posljednjih godina u gradovima se izvode isključivo kabelske, a u selima uz zračne sve više i kabelske mreže niskog napona. TS 10(20)/0,4 kV Krč nalazi se u gospodarskoj zoni Podi u Dugopolju. Mreža niskog napona trafostanice trenutačno se sastoji od 4 kabelska izvoda niskog napona kojima se napajaju gospodarski objekti u okolici trafostanice. Na slici 8 prikazana je jednopolna shema mreže niskog

The highest calculated voltage value using the model is 311,2 V, and the highest measured value in the actual network is 221,6 V, which occurred when all the grounding electrodes along the neutral conductor were disconnected. The difference occurs, as previously mentioned, due to the impossibility of defining an exact model, i.e. the precise calculation of the ground capacities of the relevant network elements and the unknown resistance of part of the electrical circuit through which the ground fault current flows. This voltage value, which in the worst case scenario can be touch voltage at a point on the network (ΔV_{Ni}), can be hazardous to life. Therefore, protection from ground faults should be adjusted in order to eliminate this danger. From all the results presented, it is concluded that from the safety standpoint it is better to ground the neutral conductor at as many points as possible, especially in karstic terrain.

4.3 Neutral conductor voltage of low voltage cable line

In recent years, exclusively low-voltage cable networks have been installed in cities, while in villages there are, together with aerial networks, an increasing number of low-voltage cable networks. The Krč 10(20)/0,4 kV substation is located in the Podi entrepreneurial zone in Dugopolje. The low-voltage substation network currently consists of 4 low-voltage cable feeders that supply commercial facilities in the surroundings of the substation. In Figure 8, a single-napona s duljinama pojedinih izvoda niskog napona. Svi kabeli niskog napona su tipa XP 00, 4x150 mm^2.

line diagram of the low-voltage network is presented with the lengths of individual low-voltage feeders. All the low-voltage cables are Type XP 00, 4x150 mm^2.



Slika 8 — Mreža niskog napona napajana iz TS 10(20)/0,4 kV Krč

Figure 8 — Low-voltage network supplied from the Krč 10(20)/0,4 kV substation

Mjerenje otpora uzemljivača trafostanice Krč izvedeno je uz odspojenu svu uzemljivačku užad položenu uz kabele niskog napona. Odspojeni su bili i svi nul-vodiči mreže niskog napona. Uzemljivačko uže uz dovodni kabelski vod srednjeg napona 10(20) kV nije bilo odspojeno od uzemljivača trafostanice, jer su bili potrebni značajni građevinski zahvati da bi se došlo do spojnog mjesta.

Radi toga je njegov utjecaj uzet u obzir kroz otpor uzemljivača same trafostanice [11]:

The measurement of the grounding resistance of the Krč substation was performed when all the grounding cables laid along the low-voltage cables were disconnected. All the neutral conductors of the low-voltage network were disconnected. The grounding cable along the medium-voltage 10(20) kV feeder cable was not disconnected from the grounding electrode of the substation because a significant construction undertaking would have been required to reach the connection point.

Therefore, its influence was taken into account through the grounding resistance of the substation [11]:

$$\boldsymbol{R}_{\mathrm{U\ TS/}} = 1{,}0\ \Omega\ . \qquad (24)$$

Kabelski vod srednjeg napona sastoji se od tri kabela 20 kV tipa XHE 49-A, 1x150 mm^2, položena u trolist. Uz pretpostavku da je specifični električni otpor zemlje jednak 1 000 Ωm izračunata je struja koja teče kroz uzemljivački sustav trafostanice za vrijeme zemljospoja [3] do [14]. Njen iznos je:

The medium-voltage cable line consists of three 20 kV cables, Type XHE 49-A, 1x150 mm^2, in trefoil formation. Assuming that the specific ground resistivity is equal to 1 000 Ωm, the current that flows through the grounding system of the substation during a ground fault is calculated [3] to [14]. Its value is:

$$\boldsymbol{I}_{\mathrm{zz}} = 28\ \mathrm{A}. \qquad (25)$$

Kabelski razvodni ormari duž pojedinih izvoda nisu uzemljeni.

The cable distribution boxes along individual feeders are not grounded.

Proračun napona nul-vodiča kabelske mreže niskog napona proveden je u skladu s poglavljem 3.1.2. U tablici 9 prikazane su neke od izračunatih vrijednosti. Pri tom su zbog usporedbe rezultata odabrane vrijednosti onih lokacija na kojima je izvršeno mjerenje.

Calculation of the neutral conductor voltage of the low-voltage cable network was conducted according to Chapter 3.1.2. In Table 9, several of the calculated values are presented. For the purpose of comparing results, values have been selected from those locations where measurement was conducted.

Tablica 9 – Izračunati iznosi napona nul-vodiča mreže niskog napona
Table 9 – Calculated values for the neutral conductor voltage of the low-voltage network

Lokacija / Location	TS / SS Krč /	KRO / Cable distribution box 2520	KRO / Cable distribution box 2590	KRO / Cable distribution box 2518
Napon nul-vodiča / Neutral conductor voltage	V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]
	24,16	24,14	24,13	24,14

Mjerenje iznosa napona nul-vodiča u mreži niskog napona provedeno je na isti način kao u prethodnom poglavlju, tj. instrumentom MI 2292 METREL. Korištena su sva tri kanala za mjerenje napona na prije spomenutim mjestima. Rezultati ovih mjerenja prikazani su u tablici 10.

Measurement of the value of the neutral conductor voltage in the low-voltage network was conducted in the same manner as in the previous chapter, i.e. using the instrument MI 2292 METREL. All three channels were used for measuring the voltage at the aforementioned points. The results of these measurements are presented in Table 10.

Tablica 10 – Izmjereni iznosi napona nul-vodiča mreže niskog napona
Table 10 – Measured values for the neutral conductor voltage of the low-voltage network

Lokacija / Location		TS / SS Krč /	KRO / Cable distribution box 2520	KRO / Cable distribution box 2590	KRO / Cable distribution box 2518
Napon nul-vodiča / Neutral conductor voltage		V_I [V]	V_{II} [V]	V_{III} [V]	V_{IV} [V]
Datum mjerenja / Date of measurement	2006-09-07	18,4	17,9	17,7	18,3
	2006-09-26	12,6	12,2	12,0	12,6

Uspoređujući dobivene rezultate vidi se da su mjerene vrijednosti nešto niže od računskih. Razlog je između ostalog i u činjenici da mjerenje otpora uzemljivača nije bilo istog dana kada su bila mjerenja napona duž nul-vodiča nmreže niskog napona. Nadalje, neposredno pred mjerenje dana 2006-09-26 pala je obilna kiša koja je utjecala na smanjenje specifičnog otpora tla, a time i na izmjerene napone čvorova.

In comparing the results obtained, it is evident that the measured values are somewhat lower than the calculated values. One of the reasons is that measurement of the grounding resistance was not conducted on the same day as when the voltage was measured along the neutral conductor of the low-voltage network. Furthermore, immediately prior to measurement, on 2006-09-26 there was abundant rainfall which reduced the specific soil resistivity and thereby affected measured node voltages.

5 ZAKLJUČAK

Uzemljivački sustav mreže niskog napona direktno je povezan s uzemljivačkim sustavom trafostanice iz koje se napaja mreža niskog napona. Sa stanovišta sigurnosti ljudi najveća opasnost od napona dodira, u slučaju zemljospoja u mreži srednjeg napona s izoliranim zvjezdištem, javlja se kod zemljospoja u pojnoj trafostanici SN/NN, jer je u tom slučaju najviši

5 CONCLUSION

The grounding system of a low-voltage network is directly connected with the grounding system of the substation from which the low-voltage network is supplied. From the standpoint of human safety, the greatest hazard is from touch voltage, in the case of a ground fault in a medium-voltage network with an isolated neutral point, which occurs during a ground fault in a supply MV/LV substation, because in such potencijal na uzemljivaču trafostanice, koji se direktno preko nul-vodiča prenosi u instalacije potrošača.

Glavni elementi koji utječu na veličinu prenesenog potencijala u mrežu niskog napona su:

- tip mreže srednjeg napona (zračna, kabelska),
- otpor uzemljivača TS SN/NN, stupova mreže niskog napona, KRO i KPO,
- izvedba mreže niskog napona (zračna, kabelska).

Jedan od faktora koji utječe na iznos otpora uzemljenja je i specifični električni otpor tla. U slučajevima njegovih niskih vrijednosti lako je postići dovoljno nizak otpor uzemljivača TS SN/NN. Dok u slučaju njegovih visokih vrijednosti (kraški tereni) ni uz velika novčana ulaganja to nije uvijek lako ostvariti.

Kabelska mreža niskog napona u odnosu na zračnu ima prednost što se uza sve kabele niskog napona polaže uzemljivačko uže (traka). Zato je opasnost od pojave previsokih napona dodira u realnoj kabelskoj mreži minimalna. Kod zračne mreže niskog napona nul-vodič se uzemljuje na više mjesta, čime se povoljno djeluje na smanjenje iznosa napona nul-vodiča mreže niskog napona.

U ovom radu su analizirane dvije distribucijske mreže HEP ODS, DP Elektrodalmacija Split kod kojih su mreže 10(20) kV u pogonu s izoliranim zvjezdištima. Za obje je zajedničko da se njihove mreže 10 kV i 0,4 kV rasprostiru kraškim terenom s vrlo visokim specifičnim električnim otporom tla koji znatno ovisi o vremenskim prilikama (padalinama). Stoga je mjerenje otpora uzemljivača vršeno u vlažnom i suhom razdoblju. Paralelno s mjerenjima provedene su analize na računalnom modelu.

Provedena istraživanja pokazala su da se cjelokupan postupak određivanja napona nul-vodiča voda niskog napona u slučaju zemljospoja na razini srednjeg napona u pojnoj TS SN/NN može izvesti sa zadovoljavajućom točnošću pomoću odgovarajućeg modela na računalu.

Naime, odstupanje računskih rezultata od provedenih mjerenja dokazuje da je računski model na strani sigurnosti. To omogućava analiziranje najnepovoljnijih slučajeva koji se mogu pojaviti u realnoj mreži. Prezentirani rezultati istraživanja ukazuju na kontinuiranu potrebu ovakvih analiza da bi se ostvarila pravilna zaštita kod zemljospoja.

cases the highest potential on the grounding electrode of the substation is directly transferred via the neutral conductor to the customers' installations.

The main elements that influence the value of the transferred potential in a low-voltage network are as follows:

- the type of the medium-voltage network (aerial, cable),
- the grounding resistance of the MV/LV substation, low-voltage network poles, cable distribution boxes and service entrance boxes,
- the type of the low-voltage network (aerial, cable).

One of the factors that affects the grounding resistance value is specific soil resistivity. When this value is low, it is easy to achieve sufficiently low grounding resistance of an MV/LV substation, while when the value is high (karstic terrain), this is not always easy to achieve, even with considerable financial investment.

A low-voltage cable network has an advantage over an aerial network in that a grounding cable (strip) is laid along all the low-voltage cables. Therefore, the hazard from excessive touch voltage occurring in an actual cable network is minimal. In a low-voltage aerial network, the neutral conductor is grounded at several points, which reduces the value of the neutral conductor voltage of a low-voltage network..

In this article, two distribution networks of the HEP Distribution System Operator (HEP ODS), Distribution Region (DP) Elektrodalmacija Split are analyzed, in which the 10(20) kV networks have isolated neutral points. For both, their 10 kV and 0.4 kV networks extend through karstic terrain with high specific soil resistivity, which significantly depends upon the weather conditions (precipitation). Therefore, measurement of grounding resistance was performed during wet and dry periods. Parallel to the measurements, analyses were performed using a computer model.

These investigations have demonstrated that the entire procedure for the determination of the neutral conductor voltage of a low-voltage line in the case of a ground fault at the medium-voltage level in an MV/LV supply substation can be conducted with satisfactory precision using an appropriate computer model.

The differences between the calculated results and the measured results demonstrate that the computer model provides a higher margin of safety. This makes it possible to analyze the worst case scenarios that can occur in an actual network. The investigation results presented indicate that such analyses should be constantly conducted in order to achieve suitable protection from ground faults.

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SMANJENJE UDARNIH STRUJA UKLOPA TROFAZNOG ENERGETSKOG TRANSFORMATORA

REDUCTION OF THE INRUSH CURRENTS OF THREE-PHASE POWER TRANSFORMERS

Goran Petrović – Tomislav Kilić – Ozren Bego, Split, Hrvatska

Udarne struje koje se javljaju prilikom uklopa energetskog transformatora mogu doseći vrlo velike iznose te uzrokovati mnogobrojne probleme u elektroenergetskom sustavu. Za istraživanje ove pojave razvijen je matematički model transformatora s uračunatim efektima zasićenja, histereze i zaostalog magnetskog toka, a opisan je i algoritam za određivanje povoljnog trenutka uklopa s ciljem smanjenja udarnih struja. Za metodu mjerenja zaostalog magnetskog toka, predložena je integracija napona sekundara pri prethodnom isklopu. Realizirana je laboratorijska maketa sustava za upravljani uklop trofaznog transformatora na kojoj su mjerenjem potvrđeni rezultati simulacija.

Inrush currents that occur during the energization of a three-phase power transformer can reach very high values and cause many problems in an power system. A mathematical model of a transformer has been developed for the investigation of this problem, taking into account the effects of saturation, hysteresis and remanent magnetic flux. An algorithm has been described for the determination of the optimal instant of energization, with the goal of reducing inrush currents. As a method for measuring remanent magnetic flux, integration of the secondary voltage during the previous de-energization is proposed. A circuit model has been prepared of a system for the controlled energization of a three-phase transformer in which the simulation results are confirmed by measurement.

Ključne riječi: petlja histereze, remanentni magnetizam, struje uklopa, transformator

Key words: hysteresis loop, inrush current, remanent magnetism, transformer

1 UVOD

Neupravljani uklop transformatora praćen je velikom nesimetrijom tokova u željeznoj jezgri. Kao posljedica takvih nesimetričnih tokova javljaju se velika izobličenja valnog oblika struje magnetiziranja, vrlo velike udarne struje uklopa, te vrlo velike istosmjerne komponente struje [1] i [2]. Problemi uzrokovani udarnim strujama uklopa mogu izazvati kvarove ili pogrešan rad osigurača, zaštitnih releja ili drugih vrsta zaštita u elektroenergetskom sustavu. Udarne struje uklopa mogu izazvati i mehanička oštećenja. Maksimalni iznos udarne struje uklopa može doseći i deseterostruki iznos nazivne struje transformatora, a moguća je pojava struja uklopa iznosa 90 % struje kratkog spoja [3]. Ovi najgori slučajevi mogu se očekivati u otprilike 10 % uklopa. Kao posljedica izobličenja valnog oblika napona tjekom prijelazne pojave mogu nastati oštećenja na osjetljivim trošilima spojenim na mrežu.Konačno, sve navedeno pridonosi bitnom smanjenju kakvoće električne energije u mreži.

Navedeni problemi pri uklopu transformatora mogu se izbjeći upravljanim uklopom. U ovom radu obrađena je metoda određivanja optimalnog trenutka uklopa na osnovi trenutačnog napona mreže odnosno njegove faze i zaostalog magnetskog toka iz prethodnog isklopa. U svrhu istraživanja optimalnog trenutka uklopa napravljen je matematički model transformatora s uračunatim efektom zaostalog magnetizma. Također je izrađena i laboratorijska maketa na kojoj su mjerenjem potvrđeni rezultati simulacija.

2 POJAVA UDARNIH STRUJA

Magnetski tok u jezgri transformatora razmjeran je integralu napona napajanja, što znači da za njim zaostaje za 90º. Ako se transformator uklopi u trenutku prolaska napona kroz nulu onda je maksimalni magnetski tok dvostruko veći od nazivnog, a tome se pridoda i zaostali magnetski tok. Amplituda toka uvijek je ista, ali tok posjeduje istosmjernu komponentu čije trajanje ovisi o radnom i induktivnom otporu kruga [4]. Na slici 1 prikazana je ovisnost električnih i magnetskih veličina u nelinearnom magnetskom krugu i načelni prikaz formiranja unutarnje putanje magnetiziranja (označeno crvenom bojom). Maksimalni tok označen je točkom 1. Kako se u toj točki mijenja derivacija magnetskog toka, ta točka pripada vrhu odgovarajuće putanje magnetiziranja, a odgovarajuća struja magnetiziranja označena je točkom 1'. Kao posljedica ekstremnog zasićenja, omjer udarne struje uklopa i nazivne struje magnetiziranja

1 INTRODUCTION

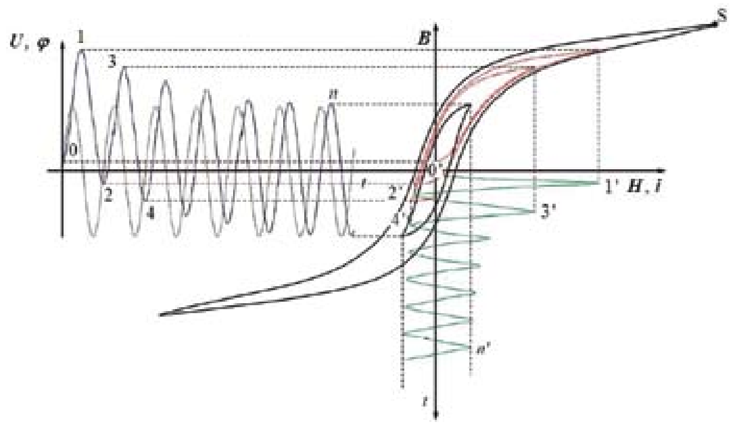
Random power transformer energization is accompanied by high asymmetry of the flux in the iron core. Due to such flux asymmetry, significant distortion of the magnetizing current waveform, very high inrush currents and a very high DC component of the inrush currents occur [1] and [2]. Problems caused by inrush currents can result in unnecessary failures or the blowing of fuses, tripping of protective relays and other types of protective devices in an power system. Inrush currents can also cause mechanical damage. Maximum inrush currents can reach ten times the amount of the rated current of a transformer as well as 90 % of the short-circuit current [3]. These worst-case scenarios can be anticipated approximately 10 % of the time. As a consequence of the distortion of the voltage waveform, damage may occur during the transient state to the sensitive loads connected to the network. Finally, all the aforementioned contributes to a significant reduction in the quality of the electricity in the network.

Such problems during the energization of a transformer can be avoided by controlled energization. In this article, a method is discussed for determining the optimal instant of energization (switching on) based upon the instantaneous network voltage, i.e. its phases, and the remanent magnetic flux from the previous de-energization. For the investigation of the optimal instant of energization, a mathematical model of a transformer was derived, incorporating the calculated effect of remanent magnetism. Furthermore, a circuit model was developed for confirming simulation results by measurement.

2 THE PHENOMENON OF INRUSH CURRENTS

Magnetic flux in the transformer core is proportional to the integral of the supply voltage, which means that it lags 90º behind the voltage. If the transformer is energized at the instant when the voltage goes through zero, the maximum magnetic flux is two times that of the rated magnetic flux, to which the remanent magnetic flux is also added. The amplitude of the flux is always the same but the flux has a dc component, the duration of which depends on the active and inductive circuit resistance [4]. In Figure 1, the relation between the electric and magnetic parameters in a nonlinear magnetic circuit is presented as well as the principle of the formation of internal minor magnetization trajectories (indicated in red). The maximum flux is indicated by Point 1. Since the derivation of the magnetic flux changes at Point 1, it corresponds to the peak of the corresponding magnetization trajectory and the corresponding magnetizing current is indicated by Point 1'. As a consequence of extreme saturation, the ratio veći je nekoliko puta od omjera udarnog toka pri uklopu i nazivnog magnetskog toka.

of the peak inrush current and the rated magnetizing current is several times greater than the ratio of the peak flux at the instant of energization and rated magnetic flux.



Slika 1 — Prikaz zavisnosti električnih i magnetskih veličina u nelinearnom magnetskom krugu i načelni prikaz formiranja unutarnje putanje magnetiziranja

Figure 1 — The relation between the electric and magnetic values in a nonlinear magnetic circuit and the principle of the formation of minor magnetization trajectories

Na istoj slici ilustrirano je nekoliko ciklusa unutarnje putanje magnetiziranja. Ako je zaostali magnetizam iznosa B_0, putanja magnetiziranja kreće iz točke 0 s pripadajućim koordinatama, $H = 0$, $B = B_0$. Kako je prirast magnetske indukcije pozitivan, putanja magnetiziranja formira se približavanjem uzlaznoj grani petlje histereze potpunog zasićenja. Prije dosezanja grane potpunog zasićenja, tj. točke S, promijeni se predznak prirasta magnetske indukcije (točka 1), pa i putanja magnetiziranja promijeni smjer. Sada se putanja počinje formirati približavanjem silaznoj grani petlje histereze potpunog zasićenja. Primjenom opisanog algoritma dolazi se u točku 2 u kojoj se ponovo mijenja predznak prirasta magnetske indukcije kao i smjer putanje magnetiziranja.

Ovaj proces se nastavlja te se konačno, završetkom prijelazne pojave, formira trajna putanja magnetiziranja odnosno petlja histereza za nazivni magnetski tok. Ta petlja nalazi se unutar petlje potpunog zasićenja i simetrična je s obzirom na ishodište koordinatnog sustava.

In the same figure, several cycles of the minor magnetization trajectories are illustrated. If the remanent magnetism is B_0, the magnetization trajectory starts from Point 0 with the corresponding coordinates, $H = 0$, $B = B_0$. Since the increment in the magnetic induction is positive, the magnetization trajectory is formed by approaching the upward trajectory of the fully saturated hysteresis loop, reaching complete saturation, i.e. Point S. The sign of the magnetic induction increment (Point 1) changes, so that the magnetization trajectory changes direction. Now the trajectory starts to be formed by approaching the downward trajectory of the fully saturated hysteresis loop. Through the application of the described algorithm, Point 2 is reached in which the sign of the magnetic induction increment changes again, as well as the direction of the magnetization trajectory.

This process continues and finally, after the transient phenomena have stopped, a magnetization curve or hysteresis loop at the rated magnetic flux is obtained. This loop is located inside the fully saturated loop and is symmetrical regarding the center of the coordinate system.

3 MATEMATIČKI MODEL UKLOPA TROFAZNOG TRANSFORMATORA

Matematički model trofaznog transformatora izveden je za najčešće korišteni tip transformatora, trostupni (europski) model kojem su pri-

3 MATHEMATICAL MODEL OF THE ENERGIZATION OF A THREE-PHASE TRANSFORMER

A mathematical model of a three-phase transformer was developed for the most frequently used type of transformer, the three-legged (European) model in marni namoti spojeni u zvijezdu s nul vodičem [5] i [6]. Sekundar nije potrebno uzimati u obzir jer se opisuje model transformatora u praznom hodu, (otvoren sekundar), što je najnepovoljniji slučaj s gledišta udarnih struja uklopa.

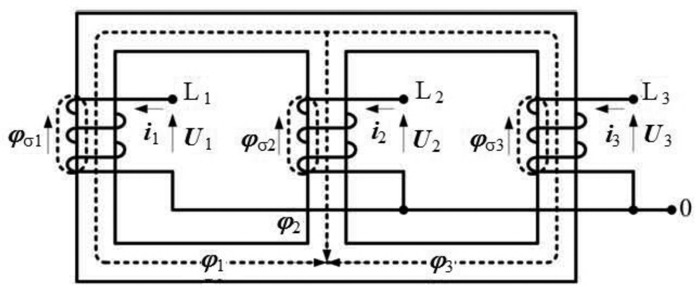
3.1 Naponske jednadžbe

Na slici 2 prikazana je pojednostavljena shema trostupnog trofaznog transformatora s primarnim namotima spojenim u zvijezdu s nul vodičem.

which the primary windings are star connected. The star point is conducted to a neutral conductor [5] and [6]. It is not necessary to take the secondary winding into consideration because the transformer model described operates under no load (open secondary), which is the worst-case scenario from the viewpoint of inrush currents.

3.1 Voltage equations

In Figure 2, a simplified diagram is presented of a three-legged three-phase transformer whose primary windings are star connected.



Slika 2 — Pojednostavljena shema trofaznog transformatora u praznom hodu
Figure 2 — A simplified diagram of a three-phase transformer operating under no load

Jednadžbe električnog kruga za navedeni transformator su:

The electric circuit equations for the transformer are as follows:

$$
\begin{aligned}
\boldsymbol{u}_1 &= R\boldsymbol{i}_1 + N\frac{\mathrm{d}(\boldsymbol{\varphi}_1+\boldsymbol{\varphi}_{\sigma 1})}{\mathrm{d}t} = R\boldsymbol{i}_1 + N\frac{\mathrm{d}\boldsymbol{\varphi}_1}{\mathrm{d}t} + L_\sigma\frac{\mathrm{d}\boldsymbol{i}_1}{\mathrm{d}t}\\
\boldsymbol{u}_2 &= R\boldsymbol{i}_2 + N\frac{\mathrm{d}(\boldsymbol{\varphi}_2+\boldsymbol{\varphi}_{\sigma 2})}{\mathrm{d}t} = R\boldsymbol{i}_2 + N\frac{\mathrm{d}\boldsymbol{\varphi}_2}{\mathrm{d}t} + L_\sigma\frac{\mathrm{d}\boldsymbol{i}_2}{\mathrm{d}t}\\
\boldsymbol{u}_3 &= R\boldsymbol{i}_3 + N\frac{\mathrm{d}(\boldsymbol{\varphi}_3+\boldsymbol{\varphi}_{\sigma 3})}{\mathrm{d}t} = R\boldsymbol{i}_3 + N\frac{\mathrm{d}\boldsymbol{\varphi}_3}{\mathrm{d}t} + L_\sigma\frac{\mathrm{d}\boldsymbol{i}_3}{\mathrm{d}t}
\end{aligned}
\tag{1}
$$

gdje je:

N — broj zavoja primarnog namota,
R — djelatni otpor primarnog namota,
L_σ — rasipna reaktancija primarnog namota.

Vektori $\boldsymbol{u}$, $\boldsymbol{i}$, $\boldsymbol{\varphi}$ predstavljaju napon, struju i magnetski tok.

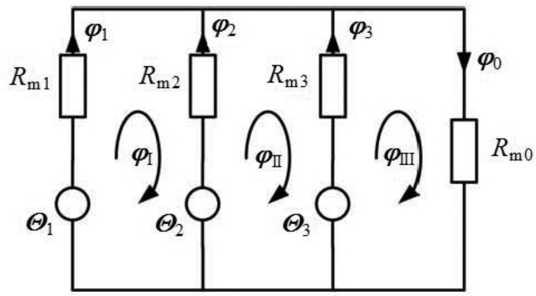
Svakom stupu magnetske jezgre odgovara jedan tok, $\boldsymbol{\varphi}_1$, $\boldsymbol{\varphi}_2$, $\boldsymbol{\varphi}_3$. Suma tokova daje tok $\boldsymbol{\varphi}_0$ koji se zatvara kroz zrak. Magnetski krug trofaznog trostupnog transformatora može se prikazati nadomjesnom shemom, slika 3.

where:

N — the number of turns of the primary winding,
R — the active resistance of the primary winding,
L_σ — the leakage reactance of the primary winding.

Vectors $\boldsymbol{u}$, $\boldsymbol{i}$, and $\boldsymbol{\varphi}$ represent voltage, current and magnetic flux.

Each flux corresponds to a leg of the magnetic core, $\boldsymbol{\varphi}_1$, $\boldsymbol{\varphi}_2$, $\boldsymbol{\varphi}_3$. The sum of the fluxes yields the flux $\boldsymbol{\varphi}_0$ which is closed through the air. The magnetic circuit of the three-legged three-phase transformer can be represented by an equivalent diagram, Figure 3.



Slika 3 — Nadomjesna shema magnetskog kruga trofaznog transformatora
Figure 3 — Equivalent diagram of the magnetic circuit of a three-phase transformer

Neka je presjek magnetske jezgre S konstantan. Duljine l_1, l_2, l_3 su srednje duljine magnetskog puta odgovarajućeg stupa. Na temelju nadomjesne sheme prikazane na slici 3, mogu se postaviti jednadžbe magnetskih krugova trofaznog trostupnog transformatora. Uz usvojene oznake:

Let the cross-section of the magnetic core S be constant. The lengths l_1, l_2, l_3 are the mean lengths of the magnetic path of the corresponding leg. On the basis of the equivalent diagram presented in Figure 3, it is possible to write the equations of the magnetic circuits of the three-phase three-legged transformer. With the following symbols,

$$\begin{aligned} \boldsymbol{\Theta}_1 &= N\boldsymbol{i}_1 & \boldsymbol{\varphi}_1 R_{m1} &= \boldsymbol{H}_1 l_1 \\ \boldsymbol{\Theta}_2 &= N\boldsymbol{i}_2 & \boldsymbol{\varphi}_2 R_{m2} &= \boldsymbol{H}_2 l_2 \\ \boldsymbol{\Theta}_3 &= N\boldsymbol{i}_3 & \boldsymbol{\varphi}_3 R_{m3} &= \boldsymbol{H}_3 l_3 \end{aligned} \tag{2}$$

jednadžbe magnetskih krugova su:

the magnetic circuit equations are as follows:

$$\begin{aligned} N\boldsymbol{i}_1 - \boldsymbol{H}_1 l_1 &= \boldsymbol{\varphi}_0 R_{m0} \\ N\boldsymbol{i}_2 - \boldsymbol{H}_2 l_2 &= \boldsymbol{\varphi}_0 R_{m0} \\ N\boldsymbol{i}_3 - \boldsymbol{H}_3 l_3 &= \boldsymbol{\varphi}_0 R_{m0} \\ \boldsymbol{\varphi}_0 &= \boldsymbol{\varphi}_1 + \boldsymbol{\varphi}_2 + \boldsymbol{\varphi}_3 \end{aligned} \tag{3}$$

Zbog nelinearne ovisnosti između magnetskog polja i magnetskog toka, odnosno magnetske indukcije rješavanje sustava jednadžbi (1) i (3) moguće je samo numeričkim postupcima. Poznavajući iznos i tendenciju magnetskog toka ($\frac{d\varphi}{dt}>0$ ili $\frac{d\varphi}{dt}<0$), odnosno magnetske indukcije može se za svaki pojedini trenutak, pomoću krivulje histereze, odrediti iznos magnetskog polja $\boldsymbol{H}$, a time i iznos faznih struja promatranog trofaznog transformatora. Zbog jednostavnijeg modeliranja pogodno je petlju histereze apoksimirati pomoću dva polinoma, koji predstavljaju uzlazni i silazni dio petlje. Dio petlje pri kojoj magnetsko polje raste je uzlazni dio, a silazni dio je onaj pri kojem magnetsko polje pada.

Due to the nonlinear relation between the magnetic field and magnetic flux, i.e. magnetic induction, the solution of the system of equations (1) and (3) is only possible by numerical procedures. Knowing the amount and tendency of the magnetic flux ($\frac{d\varphi}{dt}>0$ or $\frac{d\varphi}{dt}<0$), i.e. the magnetic induction for each individual instant, it is possible to determine the value of the magnetic field $\boldsymbol{H}$ using the hysteresis curve and thereby the values of the phase currents of the three-phase transformer. For simplified modeling, it is useful to approximate the hysteresis loop using two polynomials, which represent the upward and downward parts of the loop. The part of the loop at which the magnetic field increases is the upward part and the downward part is where the magnetic field decreases.

3.2 Modeliranje unutarnjih putanja magnetiziranja

Prilikom uklopa električnih krugova s nelinearnom magnetskom karakteristikom, dakle pri prijelaznoj pojavi, mora se poznavati hodograf [7], odnosno unutarnja putanja magnetiziranja.

U opisanom modelu pretpostavljeno je da se formiranje unutarnje putanje magnetiziranja odvija približavanjem odgovarajućem vanjskom dijelu histereze po kvadratnoj funkciji. Kako iz jedne točke putanje doći u drugu točku, uz pomoć odgovarajućeg dijela petlje histereze potpunog zasićenja, opisuje sljedeći algoritam, a ilustriran je na slici 4. Funkcija $\Delta \boldsymbol{H} = f(\boldsymbol{B})$, kvadratna je funkcija, a njeno tjeme nalazi se u točki $S(\boldsymbol{B}_S, \mathbf{H}_S)$, gdje se spajaju grane petlje histereze potpunog zasićenja. Pretpostavimo da znamo koordinate točke $T_1(\boldsymbol{B}_1, \mathbf{H}_1)$, i neka se točka $S_1(\boldsymbol{B}_1, \mathbf{H}_{S1})$ nalazi na odgovarajućem dijelu petlje potpunog zasićenja. Vrijednost funkcije $\Delta \boldsymbol{H}_1$, koja predstavlja udaljenost između točke T_1 i točke S_1 je:

3.2 Modeling of minor magnetization trajectories

During the energization of electric circuits with nonlinear magnetic characteristics, i.e. during transient phenomena, it is necessary to know the hodograph [7] or the minor magnetization trajectories.

In the described model, it is assumed that the minor magnetization trajectories are formed by approaching the corresponding part of the outer hysteresis according to the square function. The following algorithm describes how to come from one trajectory point to another, using the corresponding part of the fully saturated hysteresis loop, and is illustrated in Figure 4. The function $\Delta \boldsymbol{H} = f(\boldsymbol{B})$ is a square function and its peak is at Point $S(\boldsymbol{B}_S, \mathbf{H}_S)$, where the branches of the fully saturated hysteresis loop meet. We assume that we know the coordinates of Point $T_1(\boldsymbol{B}_1, \mathbf{H}_1)$, and let Point $S_1(\boldsymbol{B}_1, \mathbf{H}_{S1})$ be located on the corresponding part of the fully saturated loop. The value of function $\Delta \boldsymbol{H}_1$, which represents the distance between Points T_1 ,S_1 is

$$\Delta \boldsymbol{H}_1 = a(\boldsymbol{B}_1 - \boldsymbol{B}_S)^2 \tag{4}$$

Vrijednost iste kvadratne funkcije po kojoj se vrši približavanje odgovarajućem dijelu petlje histereze potpunog zasićenja u točki $\boldsymbol{B}_2 = \boldsymbol{B}_1 + \Delta \boldsymbol{B}$, bit će:

The value of the same square function, according to which the approach to the corresponding part of the fully saturated hysteresis loop is performed at Point $\boldsymbol{B}_2 = \boldsymbol{B}_1 + \Delta \boldsymbol{B}$, will be as follows:

$$\Delta \boldsymbol{H}_2 = a(\boldsymbol{B}_2 - \boldsymbol{B}_S)^2 . \tag{5}$$

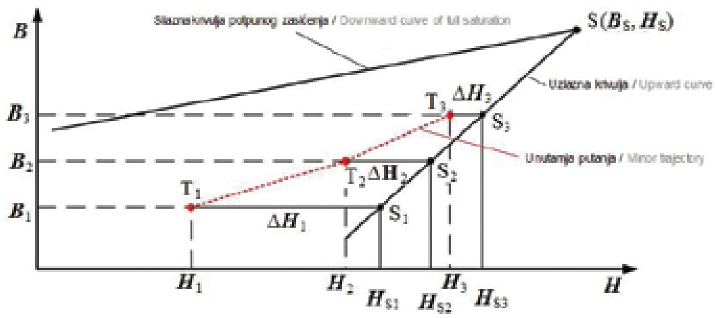
Dakle nova vrijednost funkcije na mjestu $\boldsymbol{B}_2$ bit će:

Thus, the new value of the function at Point $\boldsymbol{B}_2$ will be

$$\Delta \boldsymbol{H}_2 = \Delta \boldsymbol{H}_1 \frac{(\boldsymbol{B}_2 - \boldsymbol{B}_S)^2}{(\boldsymbol{B}_1 - \boldsymbol{B}_S)^2} = \Delta \boldsymbol{H}_1 \frac{(\boldsymbol{B}_1 + \Delta \boldsymbol{B} - \boldsymbol{B}_S)^2}{(\boldsymbol{B}_1 - \boldsymbol{B}_S)^2} , \tag{6}$$

pa nova vrijednost magnetskog polja na mjestu $\boldsymbol{B}_2$, iznosi $\boldsymbol{H}_2 = \boldsymbol{H}_{S2} - \Delta \boldsymbol{H}_2$.

and the new value of the magnetic field at Point $\boldsymbol{B}_2$ will be $\boldsymbol{H}_2 = \boldsymbol{H}_{S2} - \Delta \boldsymbol{H}_2$..



Slika 4 — Shematski prikaz algoritma za određivanje unutarnjih putanja
Figure 4 — Diagram of the algorithm for determining the minor trajectories

Na opisani način unutarnja putanja se približava odgovarajućoj krivulji potpunog zasićenja, ali je nikada ne dosegne, jer se promijeni predznak prirasta magnetske indukcije. U tom trenutku referentna krivulja postaje silazna krivulja, a postupak se odvija analogno u suprotnom smjeru. Dakle da bi se opisani algoritam mogao primijeniti potrebno je poznavati petlju histereze potpunog zasićenja.

U stacionarnom stanju vezu između magnetskog polja $\boldsymbol{H}(t)$ i magnetske indukcije $\boldsymbol{B}(t)$ opisuje jedinstvena petlja histereza koja pripada točno određenom naponu napajanja. Za promatrani transformator, moguće ju je odrediti mjereći struju magnetiziranja $\boldsymbol{i}(t)$ i inducirani napon na sekundaru $\boldsymbol{u}_2(t)$. Uz poznati broj zavoja na primaru N_1 i srednju duljinu $\boldsymbol{l}_{sr}$ magnetskog puta može se izračunati magnetsko polje:

In the manner described, the minor trajectory approaches the corresponding curve of full saturation but never reaches it because the increment sign of the magnetic induction changes. At this instant, the reference curve becomes a downward curve and the procedure takes place analogously in the opposite direction. Thus, in order to apply the described algorithm, it is necessary to know the fully saturated hysteresis loop.

In the stationary state, the relation between the magnetic field $\boldsymbol{H}(t)$ and the magnetic inductance $\boldsymbol{B}(t)$ is described by a single hysteresis loop, which belongs to a precisely specified supply voltage. For the transformer under consideration, it is possible to determine this hysteresis loop by measuring the magnetizing current $\boldsymbol{i}(t)$ and the induced voltage at the secondary winding $\boldsymbol{u}_2(t)$. When the number of turns of the primary winding N_1 and the mean length of the magnetic path $\boldsymbol{l}_{sr}$ are known, it is possible to calculate the magnetic field:

$$\boldsymbol{H}(t) = \frac{N_1\,\boldsymbol{i}(t)}{l_{\mathrm{sr}}} \qquad (7)$$

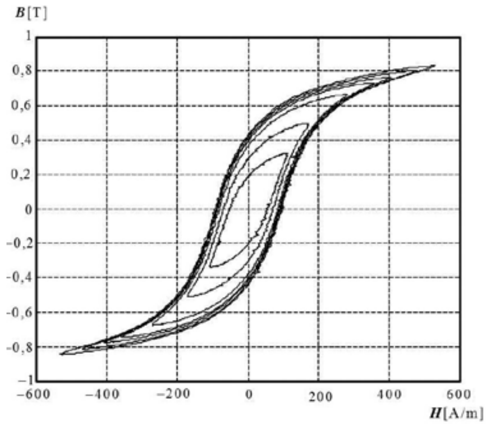
Uz poznati broj zavoja sekundara N_1 i površinu presjeka magnetskog puta S, može se izračunati magnetska indukcija:

When the number of turns of the secondary winding N_1 and the area of the cross section of magnetic path S are known, it is possible to calculate the magnetic induction:

$$\boldsymbol{B}(t) = \frac{1}{N_2 S}\int_0^t \boldsymbol{u}_2(t)\,\mathrm{d}t + \boldsymbol{B}_0 \qquad (8)$$

Grafičkim prikazom magnetske indukcije $\boldsymbol{B}(t)$ u ovisnosti o magnetskom polju $\boldsymbol{H}(t)$ dobije se hodograf koji predstavlja petlju histereze. Na slici 5 prikazano je nekoliko petlji histereze, svaka za različiti iznos struje magnetiziranja.

From the graphic representation of the magnetic induction $\boldsymbol{B}(t)$ as a function of the magnetic field $\boldsymbol{H}(t)$, a hodograph is obtained that represents the hysteresis loop. In Figure 5, several hysteresis loops are presented, each for a different magnetizing current value.



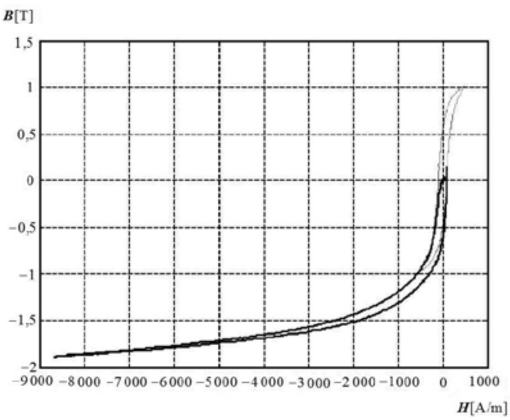
Slika 5 — Izmjerene petlje histereze pri različitim strujama magnetiziranja
Figure 5 — Measured hysteresis loops at various magnetizing currents

Magnetski krugovi energetskih transformatora projektirani su tako da im je radna točka blizu područja zasićenja, ali dovoljno daleko od područja potpunog zasićenja. Da bi ispitivana magnetska jezgra ušla u područje zasićenja potrebna je relativno velika struja magnetiziranja. Povećavajući struju magnetiziranja, osim pojačanog zagrijavanja, na krajevima namota pojavljuju se povišeni naponi koji prijete probojem izolacije. Stoga metoda snimanja potpunog zasićenja trajnom strujom nije prihvatljiva. Ukoliko se snimanje petlje histereze vrši pri uklopu transformatora, na početku prijelazne pojave koja je karakterizirana velikom udarnom strujom, moći će se u gruboj aproksimaciji smatrati da je izmjerena petlja histereze potpunog zasićenja.

Prilikom mjerenja mora se voditi računa i o efektu zaostalog magnetskog toka u transformatorskoj jezgri. Pošto se zaostali magnetski tok u jezgri ne može pouzdano izmjeriti, najjednostavnije rješenje je da on bude jednak nuli. Ovaj uvjet osigurava se razmagnetiziranjem jezgre postupno smanjujući struju magnetiziranja na nulu. Osiguravši da je zaostali tok jednak nuli izvršen je uklop transformatora u najnepovoljnijem trenutku, tako da se osigura velika udarna struja uklopa, odnosno potpuno zasićenje. Na slici 6 prikazan je graf na kojem se vidi putanja magnetiziranja koja se formira na početku prijelazne pojave (prikazana debljom crtom) te trajna petlja histereze za nazivni napon (prikazana tanjom crtom).

Magnetic circuits of power transformers are designed so that the operating point is near the saturation area but sufficiently far from the full saturation area. In order for the tested magnetic core to enter the area of saturation, relatively high magnetizing current is required. In addition to increased heating, increasing the magnetizing current results in higher voltages at the ends of the windings, which can result in insulation breakdown. Therefore, a method to record full saturation with continuous current is not acceptable. If the recording of the hysteresis loop is performed during the energization of the transformer at the beginning of the transient phenomena characterized by high inrush current, it is possible to assume that the fully saturated hysteresis loop has been measured approximately.

During measurement, it is also necessary to take the effect of the remanent magnetic flux in the transformer core into account. Since the remanent magnetic flux in the core cannot be measured reliably, the simplest solution is for it to be equal to zero. This condition is fulfilled by demagnetization, gradually decreasing the magnetizing current to zero. By insuring that the remanent flux equals zero, the energization of the transformer is performed at the most unfavorable instant, thereby assuring a high inrush current, i.e. full saturation. In Figure 6, a graph presents the magnetization trajectory formed at the beginning of the transient phenomena (thick line) and the permanent hysteresis loop at the rated voltage (thin line).



Slika 6 — Izmjerena putanja magnetiziranja za jedan period nakon uklopa (deblja crta), petlja histereza za nazivnu struju magnetiziranja (tanja crta)

Figure 6 — Measured magnetization trajectory for one period after the start of energization (thick line), hysteresis loop for rated magnetizing current (thin line)

Putanja magnetiziranja formira se između ishodišta i dijela ekstremnog zasićenja. Naravno, s vremenom se sve skupa pomiče prema ishodištu te se na kraju prijelazne pojave dobiva trajna putanja, odnosno petlja histereze koja je simetrična. Može se primijetiti da je razlika između najviše i najniže točke, u bilo kojem ciklusu, odnosno periodu ista, što je posljedica toga da je izmjenična komponenta magnetskog toka konstantna. Pomak od centra prema zasićenju posljedica je istosmjerne komponente magnetskog toka. Kako se tijekom prijelazne pojave istosmjerna komponenta prigušuje vremenskom konstantom ovisnom o radnom otporu primarnog namota, tako se i putanja magnetiziranja pozicionira oko ishodišta. Osim ove dvije komponente, na formiranje putanje magnetiziranja u prijelaznoj pojavi, utječe i zaostali (remanentni) magnetizam. Struja kao posljedica novonastalog toka, počinje se formirati iz nule. Iz navedenog slijedi da se početna točka putanje magnetiziranja općenito nalazi na osi magnetske indukcije i to unutar granica iznosa remanentnog magnetizma.

3.3 Rezultati simulacije

Opisani matematički model implementiran je u programskom paketu Matlab koristeći solver ode 113, a testiran je za transformator čiji su podaci prikazani u tablici 1. Na osnovi nazivnih podataka, standardni parametri mogu se dobiti dobro poznatim pokusima kratkog spoja i praznog hoda, a postupak određivanja petlje potpunog zasićenja opisan je u prethodnom poglavlju.

The magnetization trajectory is formed between the center of the coordinate system and the region of extreme saturation. Naturally, with time everything shifts toward the center of the coordinate system and a permanent loop or a symmetrical hysteresis loop will be formed at the end of the transient phenomena. It can be noted that the difference between the highest and the lowest points in any cycle or period is the same, which is because the AC component of the magnetic flux is constant. The shift from the center toward saturation is a consequence of the dc component of the magnetic flux. Since during the transient phenomena the dc component is damped with a time constant, which depends on the active resistance of the primary winding, the magnetization trajectories are positioned around the center of the coordinate system. In addition to these two components, remanent magnetism also affects the formation of the magnetization trajectories in transient phenomena. As a consequence of the new flux, the current starts from zero. Therefore, it follows that the starting point of the magnetization trajectory is generally located on the magnetic induction axis and within the limit of the remanent magnetism value.

3.3 Simulation results

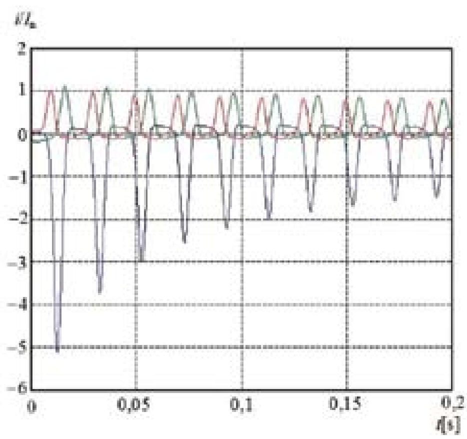
The mathematical model described has been implemented using the Matlab software package with the ODE 113 solver, and tested for the transformer for which the data are presented in Table 1. On the basis of the rated values, the standard parameters can be obtained using the well-known short-circuit and no-load tests. The procedure for determining the fully saturated loop was described in the previous chapter.

Tablica 1 — Nazivni podaci i standardni parametri trofaznog transformatora
Table 1 — Rated values and standard parameters of the three-phase transformer

Nazivna snaga / Rated power	P = 1 645 VA
Nazivni napon / Rated voltage	U_n = 380 V
Nazivna struja / Rated current	I_n = 2,5 A
Broj zavoja primara / Number of turns of the primary winding	N_1 = 557
Broj zavoja sekundara / Number of turns of the secondary winding	N_1 = 162
Impedancija kratkog spoja / Short-circuit impedance	Z_k = 8,54 Ω
Napon kratkog spoja / Short-circuit voltage	u_k = 9,74 %
Radni otpor primara pri 50 Hz / Active resistance of the primary winding at 50 Hz	$R_{\_}$ = 7,4 Ω
Rasipni induktivitet primara / Leakage inductance of the primary winding	L_σ = 3,105 mH
Ekvivalentna duljina magnetskog puta / Equivalent length of the magnetic path	l_{sr} = 0,381 m
Površima presjeka magnetske jezgre / Cross-section area of the magnetic core	S = 21,01 cm2

Opisani matematički model poslužio je pri istraživanju algoritma za određivanje optimalnog trenutka uklopa s ciljem smanjenja udarnih struja uklopa. Na slici 7 prikazane su struje uklopa trofaznog transformatora pri simulaciji nepovoljno odabranog trenutka uklopa transformatora.

The described mathematical model was used in the investigation of the algorithm for the determination of the optimal instant of energization, with the goal of reducing the inrush currents. In Figure 7, the simulated inrush currents of the three-phase transformer during unfavorable energization are shown.



Slika 7 — Struje transformatora pri nepovoljno odabranom trenutku uklopa
Figure 7 — Transformer inrush currents during unfavorable energization

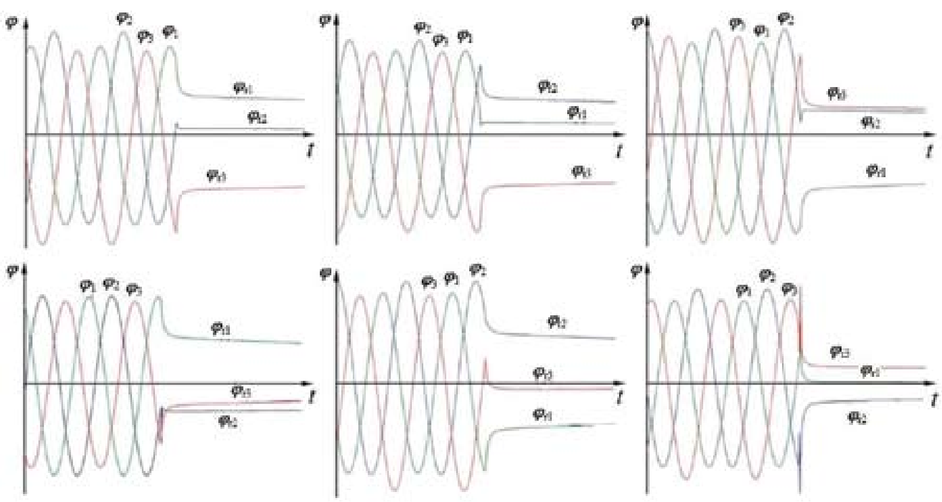
4 ODREĐIVANJE ZAOSTALOG MAGNETSKOG TOKA U JEZGRI

Temeljni problem određivanja optimalnog trenutka uklopa je mjerenje zaostalog magnetskog toka. Zaostali magneski tok je konstantan i veoma ga je teško mjeriti uobičajenim metodama za mjerenje toka. Uobičajeni senzori magnetskog polja koji rade na načelu Hallova efekta ne ugrađuju se u jezgru zbog tehnoloških i ekonomskih razloga. Teoretski moguća mjerenja tangencijalne komponente magnetskog polja neposredno na površini željezne jezgre nepouz-

4 DETERMINATION OF THE REMANENT MAGNETIC FLUX IN THE CORE

The fundamental problem in determining the optimal instant of energization is the measurement of the remanent magnetic flux. Remanent magnetic flux is constant and very difficult to measure using the customary methods for measuring flux. The usual magnetic field sensors that operate on the principle of the Hall effect are not installed in the core due to technological and economic considerations. The theoretical feasibility of measuring the tangential components of a magnetic field directly on the surface of the iron dano je zbog značajnih rasipnih tokova koji kvare sliku polja. Zato je, za detekciju zaostalog toka, prihvatljivo rješenje mjerenje napona sekundara prilikom isklopa [8]. U praznom hodu integral sekundarnog napona upravo je proporcionalan magnetskom toku u jezgri. Ako se zaostali tok ne mijenja za vrijeme dok transformator nije pod naponom, znači da će prilikom sljedećeg uklopa biti poznat njegov iznos. Na slici 8 prikazano je nekoliko izmjerenih karakterističnih stanja zaostalih magnetskih tokova prilikom isklopa trofaznog transformatora.

core are unreliable due to significant flux leakage that distorts the image of the field. Therefore, an acceptable solution for the detection of remanent flux is the measurement of the voltage at the secondary winding during de-energization [8]. During no-load operation, the integral of the secondary voltage is proportional to the magnetic flux in the core. If the remanent flux does not change during the time that the transformer is not connected to the supply voltage, its amount will be known at the time of the next energization. In Figure 8, several measured characteristic states of remanent magnetic fluxes are presented during the de-energization of the three-phase transformer.



Slika 8 — Nekoliko karakterističnih izmjerenih magnetskih tokova prilikom isklapanja trofaznog transformatora
Figure 8 — Several characteristic measured magnetic fluxes during the de-energization of the three-phase transformer

Kako se isklop ne može ostvariti trenutačno, struje isklopa donekle razgrade zaostali magnetizam. Kod većine magnetskih materijala iznos zaostalog magnetskog toka prilikom isklopa ne prelazi 50 % maksimalnog magnetskog toka koji vlada u stacionarnom stanju.

5 ODREĐIVANJE OPTIMALNOG TRENUTKA UKLOPA

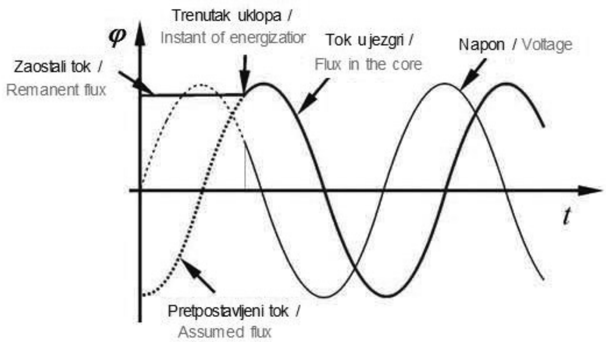
U slučaju trenutačnog (idealnog) isklopa zaostali magnetski tok bio bi jednak magnetskom toku u jezgri koji je vladao neposredno prije isklopa. Tada bi optimalni trenutak uklopa bio jednak cjelobrojnom višekratniku perioda napona napajanja. U odnosu na prolaz kroz nulu sinkronizacijskog signala, fazni kut idealnog uklopa je jednak faznom kutu prethodnog isklopa. Drugim riječima, optimalni trenutak uklopa je kada se pretpostavljeni tok, koji bi u jezgri vladao da je transformator uklopljen, izjednači sa zaostalim magnetskim tokom [9]. Optimalan

Since de-energization cannot be achieved instantaneously, de-energization currents somewhat decrease the remanent magnetism. For the majority of magnetic materials, the value of remanent magnetic flux during de-energization does not exceed 50 % of the maximum magnetic flux present in the stationary state.

5 DETERMINATION OF THE OPTIMAL INSTANT OF ENERGIZATION

In the case of instantaneous (ideal) de-energization, remanent magnetic flux would be equal to the magnetic flux in the core immediately prior to de-energization. The optimal instant of energization would then be equal to the multiple integer of the supply voltage period. The phase angle of the ideal instant of energization referenced to the zero crossing of the synchronizing signal is equal to the phase angle of the previous de-energization. In other words, the optimal instant of energization is when the assumed flux that trenutak uklopa ilustriran je na slici 9 za idealni jednofazni slučaj.

would be present in the core if the transformer were energized is equal to the remanent magnetic flux [9]. The optimal instant of energization is illustrated in Figure 9 for an ideal single-phase case.



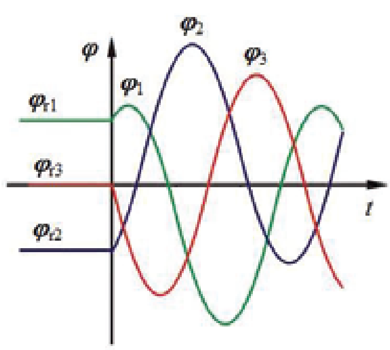
Slika 9 — Idealni trenutak uklopa jednofaznog transformatora uz zaostali magnetski tok
Figure 9 — The ideal instant of the energization of a single-phase transformer with remanent magnetic flux

Kod trofaznog transformatora, u realnoj situaciji, kada se prilikom isklopa dio zaostalog toka razmagnetizira, praktično ne postoji idealni trenutak uklopa. Za rješenje većine problema koji se javljaju prilikom uklopa, dovoljno je udarnu struju svesti na iznos manji od nazivne struje transformatora. Ova činjenica nam dopušta odabir trenutka koji nije strogo uvjetovan zahtjevom da budući magnetski tok mora biti jednak zaostalom.

Čak i ako isklop nije nastupio u istom trenutku, u sve tri faze, zbog zajedničkih magnetskih puteva za očekivati je da suma zaostalih tokova bude jednaka nuli. Uz ovu pretpostavku moguće je odrediti trenutak u kojem će budući izmjenični tokovi nakon uklopa biti dovoljno blizu zaostalim tokovima, što je na karakterističnom primjeru ilustrirano slikom 10.

For a three-phase transformer in an actual situation when a part of the remanent flux is demagnetized during de-energization, there is practically no ideal instant of energization. For the solution of the majority of problems that occur during energization, it is sufficient to reduce the inrush current to a value lower than the rated current of the transformer. This fact permits us to choose an instant that is not strictly determined by the requirement that the future magnetic flux must be equal to the remanent flux.

Even if switching off does not occur at the same instant in all three phases, due to the common magnetic paths the sum of the remanent fluxes can be expected to be equal to zero. According to this assumption, it is possible to determine the instant when the future AC fluxes after energization will be sufficiently close to the remanent fluxes, as illustrated for a characteristic example in Figure 10.



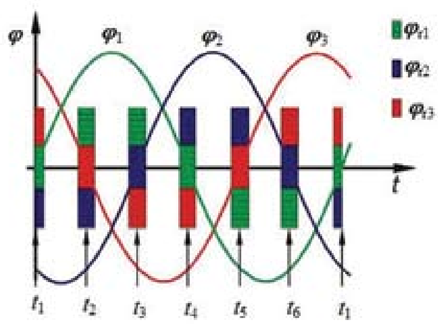
Slika 10 — Magnetski tokovi u jezgri trofaznog transformatora pri povoljno odabranom trenutku uklopa
Figure 10 — Magnetic fluxes in the core of a three-phase transformer during optimal energization

Za slučaj sa slike 10, najpovoljniji fazni kut uklopa je 180° u odnosu na magnetski tok treće faze. Ako je sinkronizacijski signal napon prve faze, koji prethodi toku iste faze za 90°, proizlazi da je najpovoljniji fazni kut uklopa 150° u odnosu na sinkronizacijski signal. U realnom slučaju treba uračunati i vrijeme odziva sklopnog aparata.

Analizom isklopa transformatora uočeno je šest karakterističnih rasporeda, zaostalog magnetskog toka. Ako je zaostali magnetski tok u prvoj fazi izrazito pozitivnog polariteta, tada zaostali magnetski tok u drugoj fazi može biti izrazito negativan, ili u blizini nule, a u trećoj fazi obrnuto. U trećem slučaju, ako je zaostali magnetski tok u prvoj fazi u blizini nule, tada zaostali magnetski tok u drugoj fazi može biti izrazito pozitivan, ili izrazito negativan, a u trećoj fazi obrnuto. U petom slučaju ako je zaostali magnetski tok u prvoj fazi izrazito negativan, tada zaostali magnetski tok u drugoj fazi može biti u blizini nule ili izrazito pozitivan, a u trećoj fazi obrnuto. Na slici 11, različitim bojama predstavljena su područja u kojima se može nalaziti zaostali magnetski tok za pojedinu fazu.

For the case in Figure 10, the most optimal phase angle for energization is 180° in reference to the magnetic flux of the third phase. If the synchronization signal is the voltage of the first phase, which leads by 90° in reference to the flux of the same phase, the most optimal phase angle for energization is 150° in reference to the synchronization signal. In an actual case, it is also necessary to take the response time of the switching unit into account.

Through analysis of the de-energization of the transformer, six characteristic patterns were noted for the remanent magnetic flux. If the remanent magnetic flux in the first phase was of markedly positive polarity, the remanent magnetic flux in the second phase could be markedly negative or near zero, and the opposite occurred in the third phase. In the third case, if the remanent magnetic flux was near zero in the first phase, the remanent magnetic flux in the second phase could be markedly positive or markedly negative, and the opposite occurred in the third phase. In the fifth case, if the remanent magnetic flux in the first phase was markedly negative, the remanent magnetic flux in the second phase could be near zero or markedly positive, and the opposite occurred in the third phase. In Figure 11, the various colors indicate the areas in which remanent magnetic flux can be found for an individual phase.



Slika 11 — Realno mogući rasporedi zaostalih tokova s pripadajućim optimalnim trenucima uklopa
Figure 11 — Actual feasible patterns of remanent fluxes with the corresponding optimal instants for energization

Dakle, svakom od šest realno mogućih stanja zaostalih tokova odgovara jedan od šest (t_1 do t_6) pripadajućih trenutaka uklopa, odnosno faznih kutova uklopa.

Thus, each of the six actual feasible states of remanent fluxes correspond to one of the six (t_1 to t_6) instants of energization, i.e. the phase angles of energization.

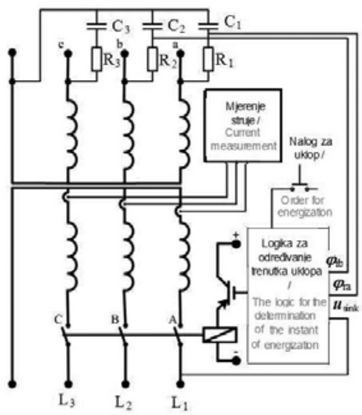
6 MAKETA SUSTAVA ZA UPRAVLJANI UKLOP

Za eksperimentalnu provjeru rezultata realizirana je laboratorijska maketa uklopa transformatora nazivnih podataka prikazanih u tablici 1. Uklop je izvršen pomoću sklopnika s vremenom odziva 9,2 ms. Sustav za mjerenje zaosta-

6 CIRCUIT MODEL FOR CONTROLLED ENERGIZATION

For the experimental testing of the results, a circuit model was developed for the energization of the transformer with the rated values presented in Table 1. Energization was performed using a switch with a response time of 9,2 ms. The system for measuring log magnetskog toka realiziran je pomoću RC člana (analogni integrator), pri čemu napon kondenzatora u određenom mjerilu predstavlja magnetski tok. Za određivanje povoljnog trenutka uklopa dovoljno je mjerenje magnetskog toka u dvije faze, jer je suma magnetskih tokova jednaka nuli. Na osnovi izmjerenih tokova te napona sinkronizacije $\boldsymbol{u}_{\text{sink}}$, logički krug određuje trenutak uklopa. Na slici 12 prikazana je shema sustava za upravljani uklop transformatora i mjerenje struje.

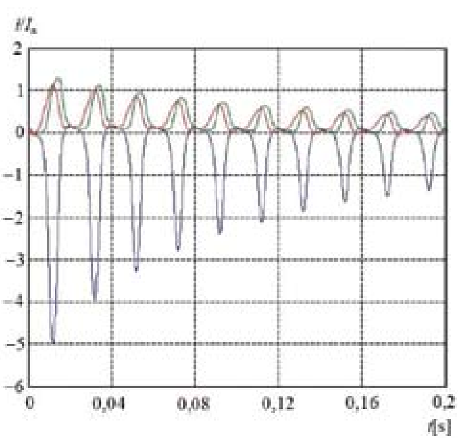
remanent magnetic flux was prepared using RC units (analogue integrators), where the voltage on the capacitors is proportional to the magnetic flux. For the determination of the optimal instant of energization, it is sufficient to measure the magnetic fluxes in two phases because the sum of the magnetic fluxes is equal to zero. On the basis of the measured fluxes and sychronizing voltage $\boldsymbol{u}_{\text{sink}}$, a logic circuit determines the instant of energization. In Figure 12, a diagram of a system for the controlled energization of a transformer and current measurement is presented.



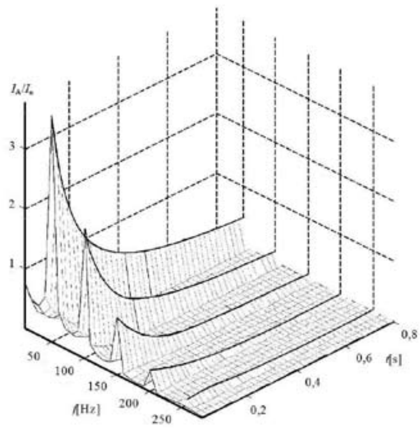
Slika 12 — Shema laboratorijske makete sustava za upravljani uklop transformatora
Figure 12 — Circuit diagram of a system for the controlled energization of a transformer

Na slici 13 prikazane su izmjerene struje u sve tri faze pri nepovoljno odbranom trenutku uklopa, a na slici 14 prikazana je vremenska promjena harmoničkog sastava struje jedne faze. Sa slika je vidljivo da je udarna struja nekoliko puta veća od nazivne struje transformatora te je bogata višim harmonicima od kojih je najizraženiji drugi.

In Figure 13, measured currents are presented in all three phases during unfavorable energization. In Figure 14, the time changes of the harmonic content of single-phase current are presented. From the figures, it is evident that the inrush current is several times greater than the rated current of the transformer and is rich in high harmonics, of which the second is predominant.



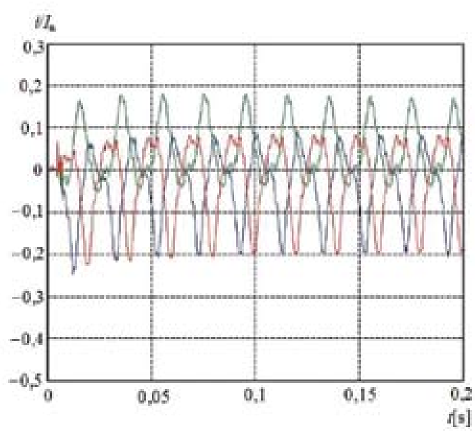
Slika 13 — Izmjereni valni oblici struja pri nepovoljno odbranom trenutku uklopa
Figure 13 — Measured current waveforms during unfavorable energization



Slika 14 — Vremenska promjena harmoničkog sastava struje jedne faze pri nepovoljno odabranom trenutku uklopa
Figure 14 — Time changes of the harmonic content of single-phase current during unfavorable energization

Na slici 15 prikazane su izmjerene struje u sve tri faze pri povoljno odabranom trenutku uklopa, pri čemu je vidljivo da u slučaju dobro odabranog trenutka uklopa gotovo ne postoje udarne struje.

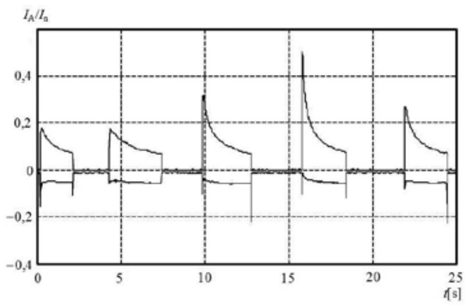
Figure 15 presents the measured currents in all three phases during optimal energization. It is evident that in the case of a well chosen energization instant, there is nearly no inrush current.



Slika 15 — Izmjereni valni oblici struja pri povoljno odbranom trenutku uklopa
Figure 15 — Measured current waveforms during optimal energization

Važan pokazatelj kakvoće izrađene makete i odabranog algoritma za određivanje optimalnog trenutka uklopa trofaznog transformatora europskog tipa, je mjerenje udarnih struja uklopa pri nekoliko uzastopnih uklopa. Radi preglednosti na slici 16 prikazana je samo envelopa struje jedne faze, tijekom nekoliko uzastopnih uklopa. Vidljivo je da pri upravljanom uklopu udarne struje ne prelaze 50 % iznosa nazivne struje transformatora.

An important quality index of the circuit model and selected algorithm for the determination of the optimal instant of the energization of a three-phase transformer of the European type is the measurement of energization inrush currents at several consecutive energizations. To simplify presentation, in Figure 16 only the single phase current envelope is presented during several consecutive energizations. It is evident that the inrush currents during controlled energization do not exceed 50 % of the values of the rated current of the transformer.



Slika 16 — Anvelopa struje jedne faze pri nekoliko uzastopnih upravljanih uklopa
Figure 16 — The envelope of a single-phase current during several consecutive controlled energizations

7 ZAKLJUČAK

U ovom radu opisan je matematički model uklopa trofaznog transformatora uz uračunate efekte petlje histereze i zaostalog magnetskog toka, za što je razvijen i poseban model za određivanje putanje krivulje magnetiziranja u prijelaznoj pojavi.

Također je opisan i sustav za mjerenje zaostalog magnetskog toka na osnovi mjerenja napona prethodnog isklopa, te je predložen algoritam za određivanje najpovoljnijeg trenutka uklopa.

Razvijena je laboratorijska maketa sustava za upravljani uklop trofaznog transformatora. Najvažniji pokazatelj kakvoće izrađene makete i odabranog algoritma za određivanje optimalnog trenutka uklopa trofaznog transformatora europskog tipa je mjerenje iznosa udarnih struja pri nekoliko uzastopnih uklopa.

Iz izmjerenih struja pri upravljanim uklopima može se zaključiti da predloženo rješenje eliminira pojavu udarnih struja koje su veće od iznosa nazivne struje transformatora.

7 CONCLUSION

In this article, a mathematical model is described for the energization of a three-phase transformer, taking into account the effects of hysteresis and remanent magnetic fluxes, for which a separate model has been prepared for determining magnetization trajectories during transient phenomena.

A system is also described for the measurement of remanent magnetic flux on the basis of measuring the voltage of the previous de-energization and an algorithm is proposed for the determination of the optimal instant of energization.

A circuit model has been developed for the controlled energization of a three-phase transformer. The most important index of the quality of the circuit model and algorithm presented for the determination of the optimal instant of the energization of a three-phase transformer of the European type is the measurement of the value of inrush currents during several consecutive energizations.

From the measured currents during controlled energizations, it is possible to conclude that the proposed solution eliminates the occurrence of inrush currents that are greater than the values of the rated transformer current.

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