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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 Vama je i peti broj časopisa Energija u 2008. godini koja je obilovala zanimljivim događajima u energetskom sektoru kako u Hrvatskoj tako i na globalnoj razini. Tako smo svjedočili jednoj od najviših svjetskih cijena barela nafte u povijesti da bi se pred sami kraj godine cijena spustila na gotovo jednu trećinu. Jednako tako pokrenuta je i inicijativa da se na razini zemalja proizvođača prirodnog plina utemelji međunarodna organizacija po uzoru na OPEC. Nesumnjivo je da će ovi događaji imati snažan utjecaj u prvom redu na cijene na veleprodajnoj razini, ali i na dostupne količine sirove nafte, a onda i prirodnog plina. Ova su događanja pravi izazov za analitičare geoenergetske politike, kako na svjetskoj razini tako i na razini Europe, ili jugoistočne Europe. Bilo bi vrlo zanimljivo čuti razmišljanja analitičara o različitim događanjima na globalnoj razini te posljedicama na vođenja energetskih politika pojedinih zemalja ili energetskih tvrtki pa smo u tom smislu otvoreni za suradnju i očekujemo vaše članke.

U ovom broju časopisa Energija objavljujemo vrlo zanimljive članke iz različitih specijalističkih područja elektrotehnike:

- Model tržišta jalovom snagom temeljen na podjeli EES-a u naponske zone i dvorazinskom optimizacijskom modelu,
- Kriteriji i metoda određivanja prioriteta za revitalizaciju prijenosne mreže,
- Kratkoročno prognoziranje opterećenja primjenom modela umjetne neuronske mreže,
- Svici – izvori homogenih magnetskih polja,
- Proračun kvazistatičkog elektromagnetskog polja složenih elektroenergetskih objekata.

U prvom članku opisana je metodologija vrjednovanja jalove snage koja se temelji na podjeli EES-a u naponske zone korištenjem metode električnih udaljenosti, čime se uspostavljaju lokalna tržišta jalovom snagom. Upravljanje naponom i jalovom snagom (U-Q regulacija) od velikog je značenja za vođenje prijenosnog sustava na tehnički, ali i ekonomski optimalan način. U članku se daje i opis metode električnih udaljenosti, a predstavljen je i originalni model tržišta jalove snage temeljen na podjeli EES-a na naponske zone. Model je testiran na primjeru hrvatskog elektroenergetskog sustava, a u radu su prikazani rezultati primjene modela, odnosno podjele elektroenergetskog sustava na naponske zone. Pokazalo se da je bitna komponenta metodologije krivulja troškova proizvodnje jalove snage o čemu i nema preciznih podataka pa se u tom smjeru trebaju nastaviti istraživanja.

Drugi članak opisuje jednu vrlo aktualnu temu vezanu uz metodologiju te kriterije određivanje prioriteta za zamjene i rekonstrukcije objekata prijenosnog sustava. Naime, sigurno i pouzdano vođenje elektroenergetskog sustava te kvalitetna opskrbe kupaca električne energije podrazumijevaju i visoka ulaganja, ne samo u izgradnju novih nego i u zamjene i rekonstrukcije postojećih objekata prijenosnog sustava. Nakon što se na temelju stvarnog stanja pojedinih komponenti utvrdi potreba nji-

Dear Readers!
You are holding the fifth issue of the journal Energija for the year 2008 which has abounded in interesting events in the energy sector in Croatia and at a global level. We have thus witnessed one of the highest ever crude oil prices per barrel only to see it plummet to nearly a third at the very end of the year. On the other hand, an initiative has been launched to form an international OPEC-style organization of gas-producing countries. These developments will surely have a powerful impact, in the first place on wholesale prices, but also on available crude oil and natural gas supplies. Therefore, the right stage is set for the analysts of geoenergy policies at international level, as well as at the level of Europe and South East Europe. Indeed, it would be interesting to see what the analysts think about various global events and their impact on the energy policies of particular countries or energy corporations, so in this respect we are open for cooperation, looking forward to receiving your articles.

In this edition of Energija we are bringing very interesting articles from different specialized fields of electrical engineering:

- Reactive power market model based on the division of the EPS into voltage zones and on the two-level optimization algorithm,
- The criteria and method of defining priorities for the revitalization of the transmission network,
- Short-term load forecasting by using the artificial neural network model,
- Coils – sources of homogeneous magnetic fields,
- Computation of quasistatic electromagnetic fields of complex electric power facilities.

The first article presents a reactive power evaluation methodology based on the division of the electric power system into voltage zones by using the electrical distance method, whereby local reactive power markets are established. Voltage and reactive power control (U-Q control) is of great importance for optimum management of the transmission system from both the technical and the economic point of view. The article also describes the electrical distance method and an original reactive power market model based on the EPS's division into voltage zones. The model has been tested on the example of the Croatian EPS and the work presents the results of the application of the model, i.e., the division of the electric power system into voltage zones. The crucial component of the methodology is shown to be the cost curve of reactive power generation, on which there are few or no precise data, so research ought to be continued in this direction.

The second article deals with a highly topical subject relating to the methodology and criteria of defining priorities for the replacement and reconstruction of transmission system facilities. Namely, secure and reliable EPS operation and quality supply of customers with electricity require major investments in both the construction of new and the replacement and reconstruction of existing transmission system facilities. Once a need for the rehove zamjene ili rekonstrukcije, potrebno je i rangirati ih kako bi se u okviru uvijek ograničenih financijskih sredstava moglo optimirati ulaganja uz zadovoljenje sigurnosnih i kvalitativnih pokazatelja. U radu je tako prikazana originalna metodologija i razvijeni kriteriji na temelju kojih se mogu odrediti liste prioriteta za revitalizaciju komponenti elektroenergetskog sustava, poglavito vodova i transformatora s ciljem održavanja zadovoljavajuće sigurnosti pogona elektroenergetskog sustava uz optimiranje troškova rada.

Treći članak u ovom broju bavi se kratkoročnom prognozom opterećenja i to procjenom vršnog opterećenja, ukupne potrošnje električne energije te procjenom krivulje opterećenja ne ulazeći u strukturne analize. Članak opisuje model za kratkoročnu prognozu opterećenja primjenom umjetne neuronske mreže kao i primjenu na predviđanje opterećenja jednog konkretnog distribucijskog područja. Umjetne neuronske mreže koriste se najčešće za rješavanje problema klasifikacije i predviđanja kada su odnosi između ulaznih i izlaznih varijabli vrlo složeni i egzaktno teško opisivi. S obzirom na stohastičku prirodu i veliki utjecaj vremenskih prilika (temperatura, vlažnost, vjetar i dr.) na potrošnju električne energije, primjena umjetnih neuronskih mreža prikladna je za kratkoročno predviđanje opterećenja elektroenergetskog sustava. Iako je opisan model tek za jedan sustav sabirnica moguće je razmatrati i više istodobnih sustava koji se mogu sinkronizirati i istodobno razmatrati.

Četvrti članak u ovom broju opisuje jedno vrlo zanimljivo područje homogenih magnetskih polja koja se koriste kod različitih instrumenata. Homogena magnetska polja koja se postižu svicima ili sustavima svitaka u širokom su rasponu od reda veličine mikrotesla, s običnim svicima, do reda veličine deset tesla sa supravodljivim svicima.Za umjeravanja instrumenata kojima se mjere magnetska polja, kao i za različite pokuse i ispitivanja u elektrotehnici, fizici, medicini, biologiji i ostalim znanstvenim i stručnim područjima, rabe se izvori poznatih homogenih magnetskih polja. Ovisno o vrijednosti željenog magnetskog polja to mogu biti permanentni elektromagneti te, češće, različiti svici koji se napajaju istosmjernom, izmjeničnom ili impulsnom strujom.

Posljednji članak opisuje teorijsku podlogu proračuna kvazistatičkog elektromagnetskog polja pomoću integralnih jednadžbi. Naime, elektromagnetska polja industrijske frekvencije, tema su brojnih radova i istraživanja, kako u svijetu tako i u Hrvatskoj, a sami proračun elektromagnetskih polja značajan je za projektiranje naprava za prijenos i pretvorbu električne energije. Nepovoljni utjecaji elektromagnetskog polja mogu se odraziti na djelovanje upravljačkih uređaja, mjernih uređaja, komunikacijskih kanala i slično, a s obzirom da su vrijednosti elektromagnetskih polja kojima se smiju izlagati ljudi jasno definirane, važno je prigodom projektiranja postrojenja utvrditi proračun elektromagnetskog polja, te tako provjeriti je li elektromegnetsko polje unutar dopuštenih graničnih vrijednosti.

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

Glavni urednik
Mr. sc. Goran Slipac

placement or reconstruction of particular components has been determined on the basis of their real condition, they will have to be sorted by priorities in order to optimize investments within the always limited funds, so as to meet security and quality requirements. This work thus presents an original methodology and develops criteria on the basis of which priority lists for the revitalization of the EPS components, primarily lines and transformers, can be defined with an aim to keep a satisfactory level of operational security of the EPS facilities and to optimize the operating costs.

The third article in this issue deals with the problems of short-term load forecasting, notably the peak load assessment, the total power consumption and the load curve assessment, without engaging in structural analyses. The article describes a model for short-term load forecasting by using the artificial neural network, and its application to load forecasting for a concrete distribution area. The artificial neural networks are mostly used in solving the problems of classification and prediction when the relations between input and output variables are highly complex and hard to describe accurately. Considering the stochastic nature and the major impact of weather conditions (temperature, humidity, wind, etc.) on electricity consumption, the application of artificial neural networks is suitable for forecasting the load of an electric power system on a short-term basis. Although the model has been prepared for one system of busbars, several simultaneous systems can be studied that can be synchronized and simultaneously reviewed.

The fourth article deals with a very interesting area, the homogeneous magnetic fields which find application with various instruments. The homogeneous magnetic fields which are produced by coils or coil systems widely vary from the microtesla order of magnitude with ordinary coils to the 10-tesla order of magnitude with superconductive coils. For calibration of the magnetic field measuring instruments and for various experiments and tests in electrical engineering, physics, medicine, biology and other scientific and technical areas the sources of known homogeneous magnetic fields are used. Depending on the value of the desired magnetic field, these can be permanent magnets or electromagnets and, more frequently, various coils fed by DC, AC or impulse current.

The last article presents the theoretical groundwork for a quasistatic electromagnetic field computation using integral equations. The electromagnetic fields of industrial frequency is the subject of many works and research studies abroad as well as at home, and the electromagnetic field computation is important in the designing of the electricity transmission and conversion devices. The adverse influences of electromagnetic fields can be reflected on the operation of control systems, measuring instruments, communication channels, etc. Since the electromagnetic field values to which persons may be exposed are clearly defined, in the designing of the facilities in question it is vital to make an electromagnetic field computation to check if the field fits into the permissible margins.

The authors of the articles in this edition of Energija are both members of the academic community and practicing engineers, which lends an added value to their contributions.

Editor-in-chief
Goran Slipac, MSc

MODEL TRŽIŠTA JALOVOM SNAGOM TEMELJEN NA PODJELI EES-A U NAPONSKE ZONE I DVO-RAZINSKOM OPTIMIZACIJSKOM ALGORITMU

REACTIVE POWER MARKET MODEL BASED ON THE DIVISION OF THE ELECTRIC POWER SYSTEM INTO VOLTAGE ZONES AND ON THE TWO-LEVEL OPTIMIZATION ALGORITHM

Tomislav Plavšić – Igor Kuzle, Zagreb, Hrvatska

U članku je predstavljena metodologija vrednovanja jalove snage koja vremenski obuhvaća djelovanje tržišta jalovom snagom u fazi kratkoročnog planiranja. Metodologija se temelji na podjeli EES-a u naponske zone korištenjem metode električnih udaljenosti, čime se uspostavljaju lokalna tržišta jalovom snagom. Unutar svakog lokalnog tržišta provodi se zasebna optimizacija troškova OPS-a po kriteriju minimalnog potrebnog plaćanja za jalovu snagu, putem proračuna optimalnih tokova snaga. Opisana optimizacija predstavlja prvi korak unutar razvijene metodologije, čiji je cilj određivanje udjela svakog od raspoloživih regulacijskih uređaja u proizvodnji jalove snage unutar svake od uspostavljenih zona. Na temelju optimalne proizvodnje jalove snage provodi se dražbeni postupak putem kojeg se određuje jedinstvena cijena proizvodnje jalove snage unutar zone. U drugom optimizacijskom koraku provodi se optimiranje cijele mreže po kriteriju minimalnih troškova nabave energije za pokriće gubitaka u mreži te po kriteriju minimalnih troškova nabave jalove energije istodobno, putem proračuna optimalnih tokova snaga. Metodologija je testirana na modelu hrvatskog EES-a, za scenarij maksimalnog opterećenja mreže. Rezultati opravdavaju predloženi pristup, a uočeni problemi ujedno su i smjernice za budući razvoj i moguća poboljšanja predložene metodologije.

The article presents a reactive power evaluation methodology which in terms of time comprises the action of the reactive power market in the stage of short-term planning. The methodology is based on the division the electric power system (EPS) into voltage zones by using the electrical distance method, whereby local reactive power markets are established. Within each local market a separate TSO cost optimization is performed by means of the optimal power flow applying the criterion of minimal required payment for reactive power. The said optimization is the first step within a developed methodology, the purpose of which is to determine the share of each of the available control systems in reactive power generation within each of the established zones. Based on optimal reactive power generation, an auction procedure is conducted by which a uniform price of reactive power generation within a zone is defined. In the second optimization step the optimization of the whole network is carried out by the criterion of minimal energy procurement costs to cover the network losses and simultaneously by the criterion of minimal reactive energy procurement costs, using the optimal power flow. The methodology has been tested on the Croatian EPS model for the maximum network load scenario. The proposed approach is warranted by the results, whereas the detected problems can at once serve as guidelines for future development and potential improvements in the proposed methodology.

Ključne riječi: električna udaljenost; optimalni tokovi snaga; pomoćne usluge sustava; regulacija napona i jalove snage; tržište jalovom snagom
Keywords: ancillary services; electrical distance; optimal power flows; reactive power market; voltage and reactive power control

1 UVOD

Upravljanje naponom i jalovom snagom ($U-Q$ regulacija) od velikog je značenja u procesu vođenja pogona elektroenergetskog sustava (EES), i s tehničkog i s ekonomskog stajališta. Održavanje vrijednosti napona u čvorištima prijenosne mreže blizu optimalne razine omogućava potrebnu sigurnost EES-a s obzirom na moguće naponske poremećaje, istodobno maksimizirajući prijenos djelatne snage i minimizirajući gubitke djelatne snage pri prijenosu.

Prije deregulacije elektroenergetskog sektora nije postojala potreba za točnim određivanjem troškova proizvodnje jalove snage, prvenstveno generatorskih jedinica, i oni su sustavno bili zanemarivani. U današnjem tržišnom okruženju uspostava odgovarajućih mehanizama plaćanja za jalovu snagu i energiju postaje ključni element u osiguranju pomoćne usluge $U-Q$ regulacije [1], [2] i [3]. Važnost dinamičke potpore jalovom snagom za stabilnost EES-a treba biti prepoznata i odgovarajuće vrednovana. Nabava pomoćne usluge $U-Q$ regulacije od raspoloživih ponuđača treba biti temeljena na tržišnim mehanizmima, a tržišnim sudionicima potrebno je uputiti ispravne cjenovne signale kako bi se osigurale investicije u sposobnost proizvodnje jalove snage planiranih proizvodnih jedinica. Potrebno je potaknuti operatore prijenosnog sustava (OPS) na ekonomično vođenje EES-a i korištenje vlastite opreme za regulaciju napona i proizvodnju jalove snage.

Predloženi su različiti pristupi rješavanju predmetnog problema [5], [6] i [7], no uspostava tržišta jalovom snagom još je uvijek predmet intenzivnog istraživanja, a mehanizmi nadoknade troškova proizvodnje jalove snage sinkronih generatora te mrežnih kompenzacijskih uređaja rijetko su gdje razvidno određeni. Tržište jalovom snagom nosi sa sobom određene probleme koje je potrebno prevladati odgovarajućim tržišnim i regulatornim mehanizmima. Prvo, lokalna priroda naponskog fenomena može stvoriti značajne razlike o pitanju naponskih prilika od regije do regije povezane električne mreže, pa čak i od čvorišta do čvorišta. Ukoliko u određenom dijelu EES-a, po prirodi deficitarnom jalovom snagom, postoji svega nekoliko ponuđača pomoćne usluge $U-Q$ regulacije vjerojatna je pojava tržišne moći (eng. *market power*). Takvo okruženje stvara OPS-u značajne troškove dok su drugi, jeftiniji ponuđači, spriječeni ravnopravno sudjelovati na tržištu radi svojeg električki udaljenog položaja. Drugi je problem složenost te nesigurnost predviđanja kratkoročnih i dugoročnih potreba EES-a za jalovom snagom. Treće, nedovoljna razvijenost mehanizama nadoknade troškova tržišnim sudionicima za sudjelovanje u $U-Q$ regulaciji dovodi u pi-

1 INTRODUCTION

Voltage and reactive power control ($U-Q$ control) is of great importance in the management of the EPS operation from both the technical and the economic point of view. The maintenance of the voltage value in the transmission network nodes at a level close to optimal ensures the required security of the EPS in view of possible voltage disruption, while at the same time maximizing active power transmission and minimizing active power transmission losses.

Before the deregulation of the electricity sector there was no need for precise determination of reactive power generation costs, primarily those of generator units, consequently they were systematically neglected. In the present-time market environment the establishment of appropriate pricing mechanisms for reactive power and energy becomes a key element in ensuring the voltage control ancillary service [1], [2] and [3]. The importance of a dynamic reactive power support for the EPS stability should be recognized and adequately assessed. The supply of the voltage control ancillary service from available bidders must be based on market mechanisms, whereas market participants should be given correct price signals in order to ensure investments in capable reactive power supply from planned generation facilities. The transmission system operators (TSO) should be encouraged to administer the EPS economically and to use their own voltage and reactive power control equipment.

For dealing with the problem under consideration various approaches have been proposed [5], [6] and [7], but the establishment of a reactive power market is still intensely studied and the mechanisms for covering the reactive power costs of the synchronous generators and the network compensation systems have been established at very few places. The reactive power market brings with it certain problems that should be resolved through appropriate market and regulatory mechanisms. First, the local nature of voltage may lead to major differences concerning voltage conditions from region to region of an interconnected electricity network, even from node to node. If in a certain part of the EPS, by nature short of reactive power, there are only few suppliers of the voltage control ancillary service, the emergence of market power is quite likely. Such an environment generates significant costs to the TSO, whereas other cheaper suppliers are prevented from market participation on equal footing because of their electrically distant position. Second, there is the problem of the complexity and uncertainty of anticipating long-term and short-term needs of the EPS for reactive power. Third, the poorly developed mechanisms for compensating the market participants for the cotanje sigurnost profita te tako sprječava pojavu novih investicija.

Lokalna priroda napona uvjetuje proizvodnju jalove snage blizu mjesta potrošnje. Prijenos jalove snage na veće udaljenosti nije niti tehnički niti ekonomski opravdan zbog velikih gubitaka pri prijenosu i smanjivanja mogućnosti prijenosa djelatne snage. Zbog toga je opravdano razmatrati uspostavu lokalnih tržišta jalovom snagom [8], [9] i [10]. Takva bi tržišta zahvaćala manje, naponski autonomne, dijelove EES-a tvoreći time zone s različitim cijenama jalove snage. Zona s višom cijenom jalove snage ne bi cjenovno utjecala na ostale zone, odnosno ne bi narušavala cijene jalove snage u ostalom dijelu EES-a. Ukupan trošak OPS-a pri korištenju pomoćne usluge $U-Q$ regulacije trebao bi stoga biti niži.

U drugom poglavlju opisana je metoda električnih udaljenosti. U trećem je poglavlju predstavljen originalni model tržišta jalovom snagom temeljen na podjeli EES-a u naponske zone. Opisana je razvijena metodologija vrednovanja pomoćne usluge $U-Q$ regulacije te dvo-razinski optimizacijski algoritam za određivanje cijena jalove snage i izračun optimalnog naponskog plana u fazi kratkoročnog planiranja.

U četvrtom poglavlju dani su rezultati testiranja predložene metodologije na modelu hrvatskog EES-a. Opisan je postupak podjele hrvatskog EES-a u naponske zone te je analiziran utjecaj uklopnog stanja mreže na granice naponskih zona hrvatskog EES-a. Dani su rezultati testiranja za scenarij maksimalnog opterećenja mreže.

2 METODA ELEKTRIČNIH UDALJENOSTI

Metoda podjele EES-a u naponski neovisne dijelove, odnosno naponske zone, putem koncepta električnih udaljenosti razvijena je radi potrebe uvođenja automatske sekundarne regulacije napona i jalove snage u sklopu francuske elektroprivrede Electricité de France (EDF) [11] i [12].

Metoda električnih udaljenosti temelji se na matrici $[\partial Q/\partial V]$, koja je sastavni dio Jacobieve matrice. Jacobieva matrica koristi se pri proračunu tokova snaga u EES-u Newton-Raphsonovom metodom [13]. Sastoji se od podmatrica prvih parcijalnih derivacija djelatne i jalove snage po kutovima napona θ i iznosima napona V u svakom čvorištu električne mreže:

sts incurred as a result of their participation in the $U-Q$ control service calls into question profit security and thus adversely affects new investment.

Due to the local nature of voltage, the generation of reactive power occurs close to the place of consumption. The transmission of reactive power to greater distances is neither technically nor economically justified due to major transmission losses and reduced active power transferability. For that reason it is justified to consider establishing local reactive power markets [8], [9] and [10]. Such markets would cover smaller, voltage-autonomous parts of the EPS by constituting zones with varying reactive power prices. A zone with higher-priced reactive power would not influence the prices in other zones, i.e., would not disrupt the reactive power prices in the rest of the EPS. The total TSO cost in using the voltage control ancillary service should hence be lower.

Section 2 describes the electrical distance method. Section 3 presents an original reactive power market model based on the EPS's division into voltage zones, a developed methodology of assessing the voltage control ancillary service, a two-level optimization algorithm for reactive power pricing, and the way of calculating an optimal voltage plan in the stage of short-term planning.

Section 4 gives the results of testing the proposed methodology on the model of the Croatian EPS, describes the procedure of dividing the Croatian EPS into voltage zones, and analyzes the impact of the network's on-state on the boundaries of the voltage zones of the Croatian EPS. Test results for the maximum network load scenario are also given.

2 ELECTRICAL DISTANCE METHOD

The method of dividing the EPS into voltage-autonomous parts or voltage zones has been developed by applying the electrical distance concept because of the need to introduce automatic secondary voltage and reactive power control in the French electricity industry, Electricité de France (EDF) [11] and [12].

The electrical distance method is based on the matrix $[\partial Q/\partial V]$, which is a constituent part of the Jacobi matrix. The Jacobi matrix is used for calculation of power flows in the EPS by means of the Newton-Raphson method [13]. It consists of the sub-matrices of the first partial derivatives of active and reactive power by voltage angles θ and voltage amounts V in each power network node:

$$\boldsymbol{J} = \begin{vmatrix} \dfrac{\partial P}{\partial \theta} & \dfrac{\partial P \cdot V}{\partial |V|} \\ \dfrac{\partial Q}{\partial \theta} & \dfrac{\partial Q \cdot V}{\partial |V|} \end{vmatrix} . \tag{1}$$

Invertiranjem matrice $[\partial Q / \partial V]$ dobiva se matrica osjetljivosti $[\partial V / \partial Q]$. Elementi matrice osjetljivosti odražavaju širenje naponskih promjena kroz promatranu mrežu zbog promjene injekcije jalove snage u određenom čvorištu. Veličinu naponske veze dvaju čvorišta mreže moguće je kvantificirati preko maksimalnog prigušenja ili slabljenja naponskih promjena između tih dvaju čvorišta. Prigušenja je moguće odrediti iz matrice osjetljivosti, dijeljenjem elemenata svakog stupca s dijagonalnim članom. Na taj se način oblikuje matrica prigušenja između svih čvorišta promatrane mreže, čiji se elementi označavaju s α_{ij} :

By inverting the matrix $[\partial Q / \partial V]$ we get the sensitivity matrix $[\partial V / \partial Q]$, the elements of which reflect the expansion of voltage changes across the observed network due to changed reactive power injection in a node. The amount of voltage link between two network nodes can be quantified through maximal induction or weakening of voltage changes between these two nodes. Induction values can be determined from the sensitivity matrix by dividing the elements of each column with the diagonal member. That is how the induction matrix between all the nodes of the observed network is formed, the elements of which are denoted α_{ij} :

$$\Delta V_i = \alpha_{ij} \cdot \Delta V_j \ , \quad \alpha_{ij} = \left(\frac{\partial V_i}{\partial Q_i} \right) / \left(\frac{\partial V_j}{\partial Q_j} \right) . \tag{2}$$

Kako bi se produkt pretvorio u zbroj, uvodi se logaritamska funkcija prigušenja kao definicija električne udaljenosti između dvaju čvorišta:

In order to transform the product into a sum, a logarithm function of induction is introduced as a definition of electrical distance between two nodes:

$$D_{ij} = -\lg \left(\alpha_{ij} \right) . \tag{3}$$

No, da bi se postigla simetričnost, električna udaljenost određena je sljedećim izrazom, koji je ujedno i konačna definicija električne udaljenosti između čvostišta i i j :

However, in order to achieve symmetry, electrical distance is defined by the following expression, which at once is the final definition of electrical distance between two nodes i and j :

$$D_{ij} = -\lg \left(\alpha_{ij} \right) . \tag{3}$$

Električna udaljenost predstavlja međuovisnost čvorišta električne mreže s obzirom na naponske promjene. Već spomenuta primjena koncepta električnih udaljenosti je određivanje naponski neovisnih dijelova EES-a. Obično se proračunava električna udaljenost čvorišta mreže prema nekolicini svojstvenih čvorišta, zvanih i pilot-čvorišta, ili prema regulacijskim čvorištima (PV čvorišta). Električne udaljenosti moguće je primijeniti i za određivanje naponskog utjecaja određenog čvori-

Electrical distance represents the interdependence of the electricity network nodes relative to voltage changes. The already mentioned application of the concept of electrical distances consists in defining the voltage-autonomous parts of the EPS. The electrical distance of the network nodes is usually calculated according to several characteristic nodes, also called pilot nodes, or according to control nodes (PV nodes). Electrical distances can also be applied in determining the šta na okolna čvorišta u svrhu određivanja mjesta instalacije kompenzacijskog uređaja.

3 MODEL TRŽIŠTA JALOVOM SNAGOM

3.1 Metodologija vrednovanja pomoćne usluge regulacije napona i jalove snage

Metodologija vrednovanja pomoćne usluge regulacije napona i jalove snage, predložena u radu, temeljena je na tržišnim osnovama uz vrednovanje i snage i energije. Pružateljima pomoćne usluge regulacije napona i jalove snage osigurava se financijska nadoknada za raspoloživi opseg proizvodnje jalove snage, odnosno tehničku spremnost za pružanje spomenute pomoćne usluge, i za induktivnu/kapacitivnu jalovu energiju proizvedenu za potrebe sustava.

Predloženi model vrednovanja pomoćne usluge regulacije napona i jalove snage ima za cilj osiguranje sigurnog i ekonomičnog pogona EES-a. Pri tome je vrlo važno prepoznavanje i ispravno vrednovanje sposobnosti kontinuirane regulacije napona u propisanom opsegu, iz koje proizlazi brza potpora sustava jalovom snagom, u normalnim i poremećenim pogonskim uvjetima. Takvu su potporu EES-u uobičajeno u mogućnosti dati samo sinkroni generatori i tu je njihovu sposobnost potrebno u normalnim pogonskim uvjetima očuvati za slučaj pojave naponskih problema u sustavu ili ozbiljnijih poremećaja. Stoga je mrežne kompenzacijske uređaje, bilo u vlasništvu OPS-a ili neke druge tvrtke, potrebno koristiti u najvećoj mogućoj mjeri kako bi se time očuvala mogućnost brze potpore sustava jalovom snagom iz sinkronih generatora, ali isto tako i smanjili troškovi OPS-a povezani s nadoknadom jalove energije proizvedene putem sinkronih generatora.

Sposobnost proizvodnje jalove snage sinkronih generatora određena je pogonskim dijagramom, slika 1, gdje je Q_{max} maksimalna induktivna jalova snaga, a Q_{min} maksimalna kapacitivna jalova snaga. P_s predstavlja zadanu djelatnu snagu sinkronog generatora dok su Q_{s_ind} i Q_{s_kap} maksimalna induktivna, odnosno kapacitivna jalova snaga, s obzirom na zadanu djelatnu snagu stroja.

Pogonski dijagram određuje dopušteno područje rada sinkronog generatora s obzirom na različita pogonska ograničenja. No, pogonski dijagram isporučen od strane proizvođača sinkronog generatora temelji se na laboratorijskom ispitivanju stroja, ili još češće na standardnom pogonskom dijagramu za taj tip stroja, te se može razlikovati od stvarnog pogonskog dijagrama stroja, posebno

voltage influence of a node on adjacent nodes with a view to determining the installation place of the reactive compensation device.

3 REACTIVE POWER MARKET MODEL

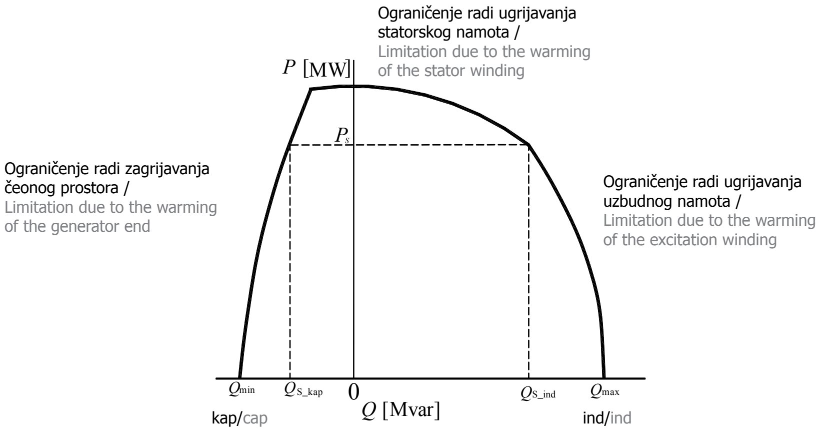
3.1 Methodology of evaluating the voltage and reactive power control support service

The methodology of evaluating the voltage and reactive power control support service, proposed in the present work, is based on market considerations along with the evaluation of both power and energy. The providers of the voltage control ancillary service are given financial compensation for the available scale of reactive power generation, or rather the technical readiness to provide the said support service, as well as for the inductive/capacitive reactive energy generated for the needs of the system.

The proposed model of evaluating the voltage control ancillary service is aimed to ensure safe and economical operation of the EPS. In this regard it is very important to recognize and correctly evaluate the capability of continuous voltage control on the prescribed scale, resulting in a quick reactive power support to the system in both normal and disrupted operating conditions. Such support to the EPS are usually capable to provide only the synchronous generators, so this capability of theirs should be preserved in normal operating conditions in the event of voltage problems or serious disruptions arising in the system. For that reason the network reactive compensation devices, owned the TSO or another company, should be utilized to maximum extent in order to preserve the capability of rapid reactive power support to the system from the synchronous generators, but also in order to cut the TSO's costs of compensation for reactive energy generated by the synchronous generators.

The capability of the synchronous generators to generate reactive power is determined by the operating diagram, Figure 1, where Q_{max} is maximal inductive reactive power, and Q_{min} is maximal capacitive reactive power, P_s is the given active power of the synchronous generator, whereas Q_{s_ind} and Q_{s_kap} are maximal inductive respectively capacitive reactive power relative to the given active power of the machine.

The operating diagram defines the synchronous generator's permissible operating range relative to different operation limitations. However, the operating diagram delivered by the manufacturer of the synchronous generator is based on the laboratory testing of the machine or, rather more typically, on the standard operating diagram for that type of machine, which may differ from the machine's real operating



Slika 1 — Pogonski dijagram sinkronog generatora
Figure 1 — Operating diagram of a synchronous generator

nakon dužeg vremena eksploatacije. Za starije strojeve pogonski dijagram trebao bi se izmjeriti u naravi, tijekom stvarnih pogonskih uvjeta.

Dodatan problem koji se javlja pri razmatranju dopuštenog područja rada sinkronog generatora je postavljanje strujnih ograničenja, tzv. limitera, prilikom puštanja stroja u pogon ili tijekom redovnih remonata i rutinskih ispitivanja, gdje se nerijetko strujni limiteri postavljaju vrlo konzervativno, pod geslom zaštite elemenata stroja od neželjenih naprezanja. Na taj način onemogućava se puno iskorištenje sinkronog generatora s obzirom na dopušteno područje rada, te tako uskraćuje potpora EES-a jalovom snagom što ponekad može biti odlučujući faktor u obrani EES-a od nastalog poremećaja. Dodatno, vlasniku proizvodnog objekta smanjuje se time prihod od pružanja pomoćne usluge regulacije napona i jalove snage.

Krivulja troškova proizvodnje jalove snage predstavlja ovisnost između proizvedene jalove snage ili energije, izražene u Mvar odnosno Mvarh, i troška uzrokovanog tom proizvodnjom, izraženog putem određene novčane valute. Potonja veličina može predstavljati i očekivanu financijsku dobit od pružanja pomoćne usluge regulacije napona i jalove snage. Krivulja troškova proizvodnje jalove snage sinkronog generatora dijeli se u tri osnovna dijela, slika 2:

— Fiksni dio odnosi se na troškove izgradnje i instalacije samog stroja, zajedno s troškovima pomoćne opreme i sustava koji omogućuju proizvodnju jalove snage. Precizno određivanje ovih troškova je upitno s obzirom na njihovo otežano razlikovanje od ostalih troškova stroja i pomoćnih sustava i opreme, budući da svi ovi elementi doprinose i osnovnoj funkcionalnosti sinkronog ge-

diagram, especially after a longer exploitation time. For older machines the operating diagram should be measured on site under real operation conditions.

Another problem arising in studying the permissible operating range of a synchronous generator is the imposition of electric current limitations, the so-called limiters, during the start-up or regular overhaul and routine testing of the machine, where quite often the limiters are adjusted very conservatively on the grounds that the machine elements must be protected from undesired stresses. The full utilization of the synchronous generator in terms of its permissible operating range is thus thwarted and the reactive power support to the EPS is thereby withheld, which may sometimes be crucial in defending the EPS against a disruption. Besides, the owner of the generation facility is deprived of a part of income from the provision of the voltage and reactive power control support service.

The cost curve of reactive power generation represents the interdependence of the generated reactive power or energy, expressed in Mvar and Mvarh respectively, and the cost caused by that generation. The latter value may represent the anticipated financial profit from the provision of the voltage and reactive power control support service. The cost curve of reactive power generation by a synchronous generator is divided into three basic parts, Figure 2:

— The fixed part relating to the construction and installation costs of the machine itself, together with the costs of the ancillary reactive power generation equipment and systems. Precision in determining these costs is questionable considering the fact that they are hard to distinguish from other costs of the machine and the ancillary equipment and systems, since all these elements are also contributing to the basic function of a synchronous generator – active power generation. One of the possible ways of deterneratora – proizvodnji djelatne snage. Jedan od mogućih načina određivanja ovih troškova je putem razlike u troškovima izgradnje stroja s obveznim i zahtijevanim faktorom snage, ukoliko je obvezan faktor snage propisan odgovarajućom regulativom, najčešće Mrežnim pravilima.

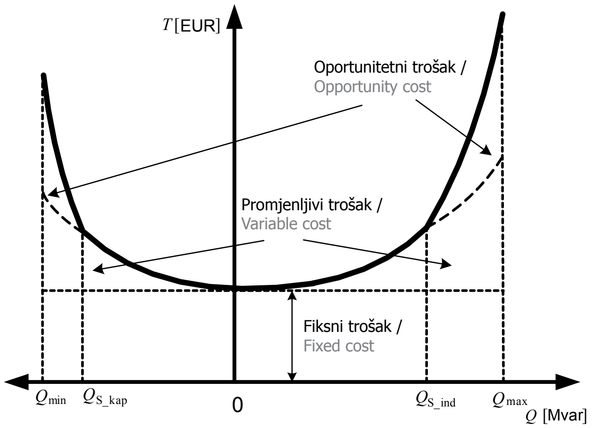
— Promjenjivi dio predstavlja troškove izazvane pretežno gubicima djelatne snage u uzbudnom i armaturnom namotu sinkronog generatora te u namotima blok transformatora. Ovisnost gubitaka u namotima o struji, odnosno izlazu jalove snage, je kvadratna (I^2R) te se tako ovisnost troškova i proizvedene jalove snage/energije može izraziti putem krivulje troška kvadratnog oblika.

— Oportunitetni trošak je trošak neiskorištene mogućnosti proizvodnje djelatne snage sinkronog generatora zbog potrebe za povećanom proizvodnjom jalove snage. Ovi se troškovi često u literaturi [1] smatraju najznačajnijim dijelom troška pružanja pomoćne usluge regulacije napona i jalove snage iz sinkronih generatora te se velika pažnja poklanja razvoju mehanizama njihovog određivanja. Oportunitetni trošak prvenstveno ovisi o tržišnoj cijeni djelatne snage, a u manjem dijelu od promjenjivog troška uzrokovanog pogonom sinkronog generatora u krajnjim rubnim dijelovima pogonskog dijagrama.

mining these costs is by means of a difference between the machine construction costs with the mandatory and with the demanded power factor, provided that the mandatory power factor is prescribed under relevant regulations, typically the Network Rules.

— The variable part representing the costs largely caused by active power losses in the excitation and armature windings of the synchronous generator and in the windings of the block transformers. The dependence of the losses in the windings on the electric current, or on the output of reactive power, is square-shaped (I^2R), so that the dependence of the costs and the generated reactive power/energy can be expressed by a square-shaped cost curve.

— The opportunity cost representing the cost of an unused opportunity to generate active power by the synchronous generator as a result of the need for increased reactive power generation. In literature [1] these costs are often considered the most important part of the cost involved in providing the voltage and reactive power control support service from the synchronous generators, so much attention is devoted to developing the mechanisms for their determination. The opportunity cost primarily depends on the market price of active power and, to a lesser extent, on the variable cost resulting from the operation of the synchronous generator in the extreme margins of the operating diagram.



Slika 2 — Krivulja troškova proizvodnje jalove snage sinkronog generatora
Figure 2 — Cost curve of reactive power production by the synchronous generator

Predloženi model procesa nabave jalove snage i energije od strane OPS-a, u sklopu osiguranja pomoćne usluge regulacije napona i jalove snage, sastoji se od četiri temeljne faze. Model je moguće prikazati vremenskom osi, gdje prva faza kreće početkom kalendarske godine ili nekog obračunski određenog perioda te završava nakon obračuna i podmirenja svih dugovanja, od OPS-a i prema OPS-u, slika 3.

The TSO-proposed model for the process of procuring reactive power and energy within the provision of the voltage and reactive power control support service consists of four basic stages. The model can be presented by a time axis where the first stage goes ahead at the start of the calendar year or an accounting period and ends after settlement of all debts from and to the TSO, Figure 3.

Putem godišnjeg natječaja za raspoloživost u pružanju pomoćne usluge regulacije napona i jalove snage osigurava se potrebna količina regulacijske jalove snage za potrebe kratkoročnog planiranja, odnosno izrade naponskog plana za sljedeći dan ili sat. Plaćanjem za regulacijsku jalovu snagu pružatelju usluge se nadoknađuje fiksni ili investicijski dio troška. Prilikom podnošenja ponude na godišnji natječaj potencijalni pružatelji usluge regulacije napona i jalove snage trebali bi svakako dostaviti važeće pogonske dijagrame sinkronih generatora koji će pružati uslugu te krivulju troškova proizvodnje jalove snage, sa specifikacijom fiksnih i promjenjivih troškova.

Temeljem tehno-ekonomske analize koja uključuje razmatranje visine fiksnih troškova te električki položaj i doprinos održavanju napona u mreži određuje se popis sinkronih generatora koji će tijekom godine pružati pomoćnu uslugu regulacije napona i jalove snage na zahtjev OPS-a. Izabranim ponuditeljima plaća se fiksna godišnja naknada za raspoloživost.

Radi uspješnog ostvarenja predložene metodologije u praksi bilo bi preporučljivo postaviti slijedeće uvjete na ponuđače:

— tijekom godine ograničiti odstupanje od krivulje troškova proizvodnje jalove snage podnesene na godišnjem natječaju sprječavajući na taj način moguće tržišne manipulacije određenih ponuđača koji bi zbog svojeg električkog smještaja bili u boljem položaju od svojih takmaca,
— nadoknadu oportunitetnih troškova vezati uz spot cijenu djelatne energije te time izbjeći određivanje visine oportunitetnih troškova od strane ponuđača.

U fazi kratkoročnog planiranja ponuđači pomoćne usluge regulacije napona i jalove snage podnose svoje ponude OPS-u, putem dostave raspoloživog regulacijskog opsega jalove snage u poduzbudi i naduzbudi, u sklopu krivulje troškova proizvodnje jalove snage. Na temelju podnesenih krivulja troškova te predvidivog pogonskog stanja za svaki sat u sljedećem danu, putem optimizacijskog proračuna određuje se naponski plan, ili vozni red napona, za svaki generator koji sudjeluje u pružanju pomoćne usluge regulacije napona i jalove snage.

Nakon toga provodi se dražbeni postupak uzimajući pri tome u obzir samo one generatore koji su odabrani za pružanje usluge putem optimizacijskog proračuna. Dražbenim postupkom određuje se jedinstvena marginalna cijena jalove energije. Jedinstvenu marginalnu cijenu jalove energije predstavlja najviša marginalna cijena odabranih generatora. Svakom odabranom generatoru

Through a yearly tender for the available provision of the voltage and reactive power control support service a required quantity of control reactive power is secured for the needs of short-term planning or the preparation of a voltage plan for the next day or hour. Payment for control reactive power compensates the service provider for the fixed or investment part of the cost. When submitting their bids during the yearly tender procedure the potential providers of the voltage and reactive power control service should not fail to present the valid operating diagrams of the synchronous generators which will render the service and the cost curve of reactive power generation with a specification of fixed and variable costs.

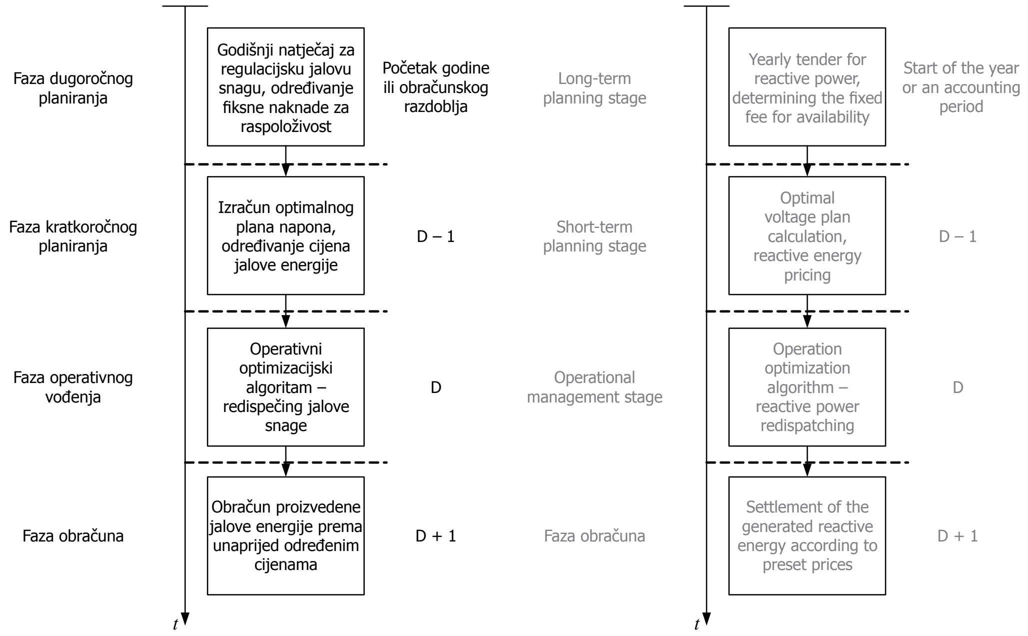
Based on a technical and economic analysis, which includes a study of the amount of fixed costs as well as the electrical position and contribution to the maintenance of voltage in the network, a list of synchronous generators is compiled which during the year will provide the voltage control ancillary service at the TSO's request. The selected bidders are paid a fixed annual fee for availability.

For the proposed methodology work in practice, it is recommendable to impose the following conditions on the bidders:

— during the year restrict deviations from the cost curve of reactive power generation submitted at the annual competition, thus preventing possible market manipulations by some bidders who, owing to their electrical position, would have an edge on their competitors,
— link the reimbursement of opportunity costs to the spot price of active energy and thereby avoid that the amount of opportunity costs is determined by the bidders.

In the short-term planning stage the bidders of the voltage and reactive power control support service are submitting their bids to the TSO, presenting the available reactive power control range in subexcitation and overexcitation within the cost curve of reactive power generation. Based on the submitted cost curves and the predictable operation state for every hour in the next day, the voltage plan or the voltage timetable is defined through optimization for every generator participating in the provision of the voltage and reactive power control support service.

After that an auction procedure is conducted, taking into account only those generators which have been selected for the provision of the service by means of optimization. The auction procedure defines the uniform marginal price of reactive energy. The uniform marginal price of reactive energy is represented by the highest marginal price of the selected generators. In the end, each selected ge-



Slika 3 — Model procesa nabave jalove snage i energije

Figure 3 — Model of reactive power and energy procurement process

u konačnici se proizvedena jalova energija plaća prema jedinstvenoj marginalnoj cijeni.

Za svaku se naponsku zonu provodi odvojeni dražbeni postupak, temeljen na zonskom optimizacijskom proračunu, te time postižu različite marginalne cijene jalove energije u svakoj naponskoj zoni.

Predložena metodologija putem proračuna optimalnih tokova snaga uvažava stvarno pogonsko stanje EES-a. Stoga na cijene jalove energije značajno utječu naponski problemi ili nedovoljan broj izvora jalove snage. U slučaju postojanja takvih problema cijene jalove energije mogu biti izrazito visoke. Zonskim pristupom cijene jalove energije u nekoj regiji ne utječu na cijene jalove energije u ostalim regijama. Na taj se način postižu ispravni cjenovni signali prema tržišnim sudionicima i samom OPS-u, a za očekivati je da će i ukupni troškovi OPS-a za osiguranje pomoćne usluge regulacije napona i jalove snage biti niži. U konačnici se provodi cjelovita optimizacija, uzimajući u obzir i troškove nabave energije za pokriće gubitaka u mreži i troškove nabave jalove energije. Predloženi optimizacijski algoritam za određivanje naponskog plana u fazi kratkoročnog planiranja detaljnije je opisan u sljedećem poglavlju.

U fazi operativnog vođenja EES-a, tijekom normalnih pogonskih uvjeta, periodički se pokreće proračun optimalnih tokova snaga i po potrebi dodatno podešava postavne vrijednosti napona regulacijskih i kompenzacijskih uređaja s obzirom na trenutačno pogonsko stanje EES-a. U trenutku

nerator is paid for the generated reactive energy according to the uniform marginal price.

For each voltage zone a separate auction procedure is conducted, based on zonal optimization and thereby different marginal prices of reactive energy are achieved in each voltage zone.

The proposed methodology using the optimal power flow takes heed of the EPS's real operation state. Hence the prices of reactive energy are significantly influenced by voltage problems or by insufficient number of reactive power sources. In the event of such problems the prices of reactive energy may be excessively high. The zonal approach excludes the influence of the prices of reactive energy in one region on those in other regions. In this way correct pricing signals are sent out towards both the market participants and the TSO, and it is likewise to be expected that the total TSO's costs for the provision of the voltage and reactive power control support service will be lower. In the final analysis a comprehensive optimization is carried out, also taking into account the energy procurement cost for covering the network losses and the reactive energy procurement costs. The proposed optimization algorithm for defining the voltage plan in the short-term planning stage is described in more detail in the next section.

In the stage of operational management of the EPS, under normal operation conditions, the optimal power flow calculation is periodically initiated and, as required, the set voltage values of control and reactive compensation devices are additionally prelaska u poremećeno pogonsko stanje optimizacijski proračun je potrebno blokirati, a automatske upravljačke funkcije treba preuzeti algoritam sa sigurnosnom zadaćom kao funkcijom cilja.

U fazi obračuna svim se pružateljima pomoćne usluge regulacije napona i jalove snage u promatranom razdoblju obračunava raspoloživost te proizvedena induktivna, odnosno kapacitivna jalova energija, na temelju prethodno određenih cijena. Prema predloženom modelu pomoćna usluga regulacije napona i jalove snage obračunava se putem tri cijene:

- cijena za raspoloživost ili regulacijsku snagu – pokriva fiksni dio troškova proizvodnje jalove snage, predstavlja fiksnu godišnju naknadu određenu kroz proces godišnjeg natječaja,
- cijena za proizvedenu induktivnu/kapacitivnu jalovu energiju – pokriva promjenjivi dio troškova proizvodnje jalove snage, predstavlja marginalnu cijenu određenu u fazi kratkoročnog planiranja putem dražbenog postupka, te
- cijena oportunitetnog troška - pokriva oportunitetni dio troškova proizvodnje jalove snage, određuje se u fazi obračuna na temelju dnevnih ili satnih spot cijena djelatne energije.

Jedno od važnih pitanja koje je potrebno uzeti u obzir pri uspostavi tržišnih mehanizama za osiguranje pomoćne usluge regulacije napona i jalove snage je sprječavanje tržišne moći određenih ponuđača, koji koriste svoj povoljan električki položaj u EES-u i pogonske prilike, te prijavljuju neopravdano visoke marginalne troškove svojih usluga.

Unutar predloženog modela ugrađena su tri mehanizma koja mogu djelomično spriječiti pojavu tržišne moći:

- određivanje zonskih cijena jalove energije,
- ograničeno odstupanje od krivulje troškova proizvodnje jalove snage podnesene na godišnjem natječaju i
- određivanje cijene oportunitetnog troška temeljen spot cijene djelatne energije.

No, učestali povećani troškovi nabave jalove energije dobar su cjenovni signal OPS-u da su nužne investicije u odgovarajuće kompenzacijske uređaje u određenom dijelu EES-a.

3.2 Dvo-razinski optimizacijski algoritam za određivanje cijena jalove snage i izračun naponskog plana u fazi kratkoročnog planiranja

Optimizacijski algoritam predložen u članku ima dva osnovna cilja: prvi, određivanje jedinstvenih zonskih cijena jalove energije i drugi, određivanje

adjusted in dependence on the current operation state of the EPS. Optimization should be blocked at the moment of transition to a disrupted operation state and the automatic control functions should be assumed by the algorithm with the safety task as a goal function.

In the settlement stage, for all the providers of the voltage and reactive power control support service in the observed period the availability is worked out plus the generated inductive or capacitive reactive energy, based on preset prices. According to the proposed model, the voltage and reactive power support service is settled via three prices:

- the availability or control power price – covers the fixed part of reactive power generation, it is the fixed annual fee defined during the annual tendering process,
- the price for the generated inductive/capacitive reactive energy – covers the variable part of reactive power generation, it is the marginal price defined in the short-term planning stage through the auction procedure, and
- the price of opportunity costs – covers the opportunity costs of reactive power generation, it is set in the settlement stage on the basis of daily or hourly spot prices of active energy.

An important matter to be considered in introducing market mechanisms for the provision of the voltage and reactive power control support service is how to prevent the market power of certain bidders who are using their advantageous electrical position in the EPS and the prevailing operation conditions by reporting unjustifiably high marginal costs of their services.

The proposed model incorporates three mechanisms that can partially offset the occurrences of market power:

- setting the zonal prices of reactive energy,
- restricted deviation from the cost curve of reactive power generation submitted at the annual competition, and
- setting the price of opportunity cost based on the spot price of active energy.

However, the repeatedly increased costs of reactive energy procurement tend to send a good price signal to the TSO that investments in some reactive compensation devices in a certain part of the EPS are necessary.

3.2 The two-level optimization algorithm for reactive power pricing and the voltage plan computation in the short-term planning stage

The optimization algorithm as proposed in the present article has two general goals: first, to define naponskog plana temeljem minimiziranja ukupnih troškova OPS-a. Algoritam se sastoji od dva koraka pri čemu su zonske cijene jalove energije, kao izlaz prvog koraka optimizacije, ujedno nužan ulaz za drugi optimizacijski korak. Drugi optimizacijski korak istodobno minimizira troškove nabave energije za pokriće gubitaka u mreži i troškove plaćanja za jalovu energiju tvoreći time problem višekriterijskog optimiranja.

Korištenje predloženog optimizacijskog algoritma predviđeno je u fazi kratkoročnog planiranja, slika 4, no moguće ga je koristiti i u fazi operativnog vođenja EES-a za podešavanje naponskog plana s obzirom na trenutačno pogonsko stanje. Za određeni vremenski period unutar dana, najčešće jedan sat, potrebno je proračunati optimalan naponski plan temeljem sljedećih ulaznih parametara:

- prognoze opterećenja,
- očekivane topologije mreže,
- planiranih vrijednosti proizvodnje djelatne snage agregata u pogonu, te
- planiranih vrijednosti prekogranične razmjene električne snage.

Prvo je potrebno provesti sigurnosnu analizu stanja mreže s obzirom na ulazne podatke, što se izvodi putem standardnog proračuna tokova snaga i $n-1$ analize sigurnosti. Ako je analizom sigurnosti utvrđeno da su parametri EES-a u danom vremenskom periodu unutar propisanih ograničenja, moguće je pristupiti optimizacijskom proračunu, s ciljem minimiziranja troškova sustava i pripreme podloge za osiguranje pomoćne usluge regulacije napona i jalove snage putem tržišnih mehanizama.

Minimiziranje troškova proizvodnje jalove snage temeljem krivulja troškova sinkronih generatora i kompenzacijskih uređaja, uz poštivanje sigurnosnih ograničenja EES-a, provodi se u prvom optimizacijskom koraku. Problem se rješava putem proračuna optimalnih tokova snaga [14] i [15]. Model tržišta jalovom snagom treba svakako uzeti u obzir električki položaj izvora jalove snage osiguravajući se na taj način od korištenja udaljenih generatora s niskim troškovima u svrhu regulacije napona u sasvim drugom dijelu EES-a. Takva je mogućnost izrazito nepovoljna sa stajališta vođenja EES-a budući da je i tehnički i ekonomski neopravdano prenositi jalovu snagu na veće udaljenosti. Stoga se predlaže zonski pristup pri čemu svaka naponska zona djeluje kao zasebno tržište jalovom snagom te se i optimizira zasebno.

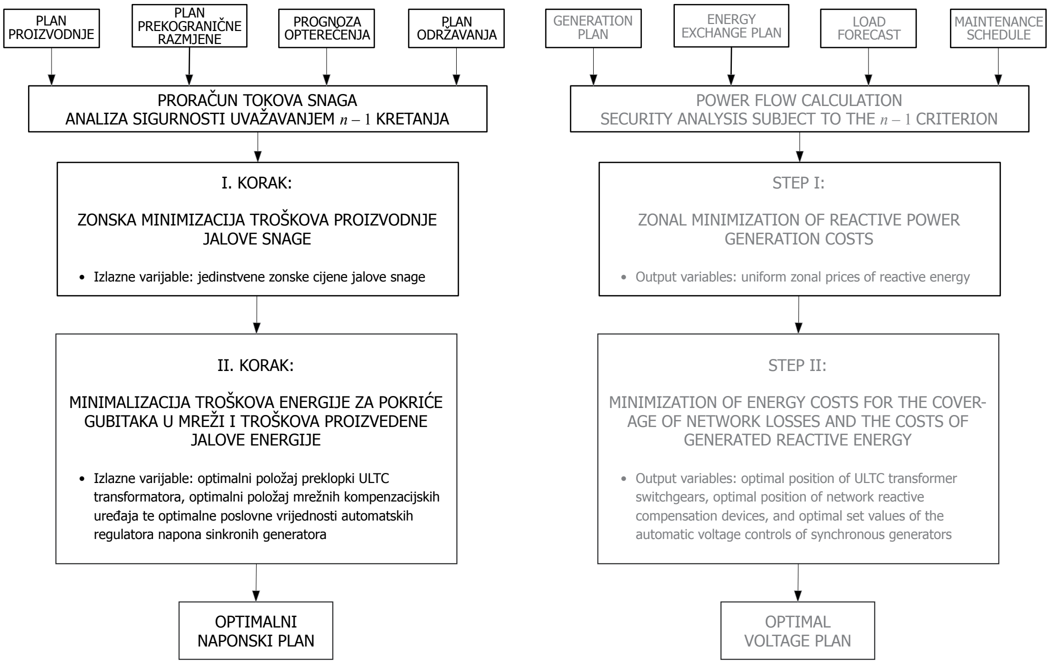
the uniform zonal prices of reactive energy and, second, to define the voltage plan based on minimized total costs of the TSO. The algorithm consists of two steps, where the zonal prices of reactive energy as the output of the first optimization step are at once the required input for the second optimization step. At the same time, the second optimization step minimizes the energy procurement costs for the coverage of network losses and the reactive energy payment costs, thus ushering the problem of multi-criterion optimization.

The proposed optimization algorithm is designed for use in the short-term planning stage, Figure 4, but it can also be used in the operational management stage for adjusting the voltage plan relative to the current operation state. For a particular period of time, mostly one hour, it is necessary to calculate the optimal voltage plan based on the following input parameters:

- load forecast,
- expected network topology,
- planned values of active power generation by units in operation, and
- planned values of transboundary electricity exchange.

The first thing to do is a security analysis of the state of the network relative to input data, which is done by means of the standard power flow calculation and the $n-1$ security analysis. If the security analysis finds that the EPS parameters in a given period of time are within the prescribed limitations, it is possible to carry out optimization aimed to minimize the costs of the system and documentation for the provision of the voltage and reactive power control support service via market mechanisms.

The minimization of the reactive power generation costs based on the cost curves of the synchronous generators and reactive compensation devices, subject to abidance by the EPS's safety restrictions, takes place in the first optimization step. The problem is solved by means of the optimal power flow [14] and [15]. The reactive power market model must make allowance for the electrical position of the sources of reactive power, thus securing itself against the use of remote low-cost generators for voltage control in an entirely different part of the EPS. Such a possibility is clearly unfavorable in terms of EPS management, as it is both technically and economically unjustified to transmit reactive power to greater distances. Hence a zonal approach is proposed, where every voltage zone is functioning as a separate reactive power market and is also separately optimized.



Slika 4 — Dvo-razinski optimizacijski algoritam u fazi kratkoročnog planiranja

Figure 4 — Two-level optimization algorithm in the short-term planning stage

Problem zonskog minimiziranja troškova proizvodnje jalove snage ima sljedeći oblik:

Minimiziranje zonske funkcije cilja oblika:

The problem of the zonal minimization of reactive power generation costs has the following form:

Minimization of the zonal goal function of the following form:

$$F_Z(x,u)=\sum_{i=1}^{N_{gz}} f_{CQi} = \sum_{i=1}^{N_{gz}} \left(c_{2i}\cdot Q_{gi}^2 + c_{1i}\cdot Q_{gi} + c_{0i} \right), \tag{5}$$

gdje je:

f_{CQi} – funkcija troška proizvodnje jalove snage generatora u čvorištu i,
c_{0i} – koeficijent kvadratne funkcije troška [EUR] generatora u čvorištu i,
c_{1i} – koeficijent kvadratne funkcije troška [EUR/Mvar] generatora u čvorištu i,
c_{2i} – koeficijent kvadratne funkcije troška [EUR/Mvar^2] generatora u čvorištu i,
N_{gz} – broj generatora unutar naponske zone z,

S obzirom na sljedeća ograničenja tipa jednakosti (jednadžbe tokova snaga):

where:

f_{CQi} – reactive power generation cost function of the generator in node i,
c_{0i} – coefficient of the square function of the cost [EUR] of the generator in node i,
c_{1i} – coefficient of the square function of the cost [EUR/Mvar] of the generator in node i,
c_{2i} – coefficient of the square function of the cost [EUR/Mvar^2] of the generator in node i,
N_{gz} – number of generators within the voltage zone z.

Considering the following limitations of equality type (power flow equations):

$$0=\sum_{j=1}^{n} U_i\cdot U_j\cdot Y_{ij}\cos\left(\theta_{ij}+\delta_j-\delta_i\right)-P_{Gi}-P_{Di}, \tag{6}$$

$$0=\sum_{j=1}^{n} U_i \cdot U_j \cdot Y_{ij} \sin\ (\theta_{ij}+\delta_j-\delta_i)-Q_{\mathrm{G}i}-Q_{\mathrm{D}i} \tag{7}$$

i ograničenja tipa nejednakosti:

and the limitations of inequality type:

$$Q_{\mathrm{G}i\min} < Q_{\mathrm{G}i} < Q_{\mathrm{G}i\max}\ , \tag{8}$$

$$U_{i\min} < U_i < U_{i\max}\ , \tag{9}$$

$$t_{ij\min} < t_{ij} < t_{ij\max}\ , \tag{10}$$

$$\left|S_{ij}\right|^2-\left|S_{ij\max}\right|^2 \leq 0\ , \tag{11}$$

gdje je:

U_i – iznos napona u čvorištu i,
δ_i – kut napona u čvorištu i,
$P_{\mathrm{G}i}$ – proizvodnja djelatne snage u čvorištu i,
$Q_{\mathrm{G}i}$ – proizvodnja jalove snage u čvorištu i,
$P_{\mathrm{D}i}$ – opterećenje djelatnom snagom u čvorištu i,
$Q_{\mathrm{D}i}$ – opterećenje jalovom snagom u čvorištu i,
Y_{ij} – admitancija elementa mreže između čvorišta i i j,
θ_{ij} – fazni kut admitancije Y_{ij},
$Q_{\mathrm{G}i\min}$ – ograničenje proizvodnje kapacitivne jalove snage u čvorištu i (slika 1),
$Q_{\mathrm{G}i\max}$ – ograničenje proizvodnje induktivne jalove snage u čvorištu i (slika 1),
$U_{i\min}, U_{i\max}$ – ograničenja vrijednosti napona u čvorištu i,
t_{ij} – položaj preklopke transformatora između čvorišta i i j,
$t_{ij\min}, t_{ij\max}$ – ograničenja položaja preklopke transformatora između čvorišta i i j,
S_{ij} – vrijednost toka prividne snage na elementu mreže između čvorišta i i j.

Pri tom su sve električne veličine prikazane u jediničnim vrijednostima (per unit – p.u.).

Izlazne varijable prvog optimizacijskog koraka su optimalne vrijednosti proizvodnje jalove snage sinkronih generatora i mrežnih kompenzacijskih uređaja prema kriteriju minimalnih troškova. Mrežni kompenzacijski uređaji se promatraju kao izvori jalove snage s vrlo niskim troškovima, neovisnima o veličini proizvodnje (marginalni troškovi

where:

U_i – amount of voltage in node i,
δ_i – voltage angle in node i,
$P_{\mathrm{G}i}$ – active power generation in node i,
$Q_{\mathrm{G}i}$ – reactive power generation in node i,
$P_{\mathrm{D}i}$ – active power load in node i,
$Q_{\mathrm{D}i}$ – reactive power load in node i,
Y_{ij} – admittance of network elements between nodes i and j,
θ_{ij} – admittance phase angle Y_{ij},
$Q_{\mathrm{G}i\min}$ – limitation of capacitive reactive power generation in node i (Figure 1),
$Q_{\mathrm{G}i\max}$ – limitation of capacitive inductive power generation in node i (Figure 1),
$U_{i\min}, U_{i\max}$ – limitations of voltage values in node i,
t_{ij} – position of transformer switchgear between nodes i and j,
$t_{ij\min}, t_{ij\max}$ – limitations of transformer switchgear position between nodes i and j,
S_{ij} – apparent power flow value on the network element between nodes i and j.

All the electrical values above are shown in per unit (p.u) values

The output variables of the first optimization step are the optimal values of the reactive power generation by the synchronous generators and the network reactive compensation devices in accordance with the minimal cost criterion. The network reactive compensation devices are viewed as very low-cost reactive power sources independent of the scale of generation (the marginal costs of reactive power generation are constant). Their use is thus maximized through calculation, whereas proizvodnje jalove snage su konstantni). Na taj se način kroz proračun maksimizira njihova uporaba, a određena pričuva jalove snage ostaje očuvana unutar sinkronih generatora radi otklanjanja mogućih naponskih poremećaja u operativnoj fazi vođenja EES-a.

U proračun se ulazi s pretpostavkom da je moguć nesmetan rad svakog od raspoloživih sinkronih generatora u bilo kojoj točki odgovarajućeg pogonskog dijagrama, te da je svaki ponuditelj spreman na zahtjev OPS-a smanjiti proizvodnju djelatne snage svojih sinkronih generatora s ciljem proizvodnje dodatne jalove snage. Za potrebe opisanog slučaja smanjenje izlaza djelatne snage modelirano je unutar proračuna putem linearne aproksimacije ograničenja pogonskog dijagrama radi zagrijavanja uzbudnog namota:

a certain reactive power reserve remains preserved within the synchronous generators for the elimination of possible voltage disruptions in the operational stage of EPS management.

Calculation is done under the assumption that an undisturbed operation of each of the available synchronous generators in possible at any point of the respective operating diagram and that at the TSO's request every bidder is ready to reduce the active power generation of its synchronous generators with an aim to generate additional reactive power. For the needs of the described case, the decreased active power output is modeled within the calculation by means of a linear approximation of the operating diagram limitations due to the warming of the excitation winding:

$$Q_{\mathrm{G}i} = a \cdot P'_{\mathrm{G}i\mathrm{S}} + b, \tag{12a}$$

$$Q_{\mathrm{G}i\mathrm{S}} < Q_{\mathrm{G}i} < Q_{\mathrm{G}i\max} \ , \tag{12b}$$

$$P_{\mathrm{G}i\mathrm{S}} < P'_{\mathrm{G}i\mathrm{S}} < P_{\mathrm{G}i\min} \ , \tag{12c}$$

gdje je:

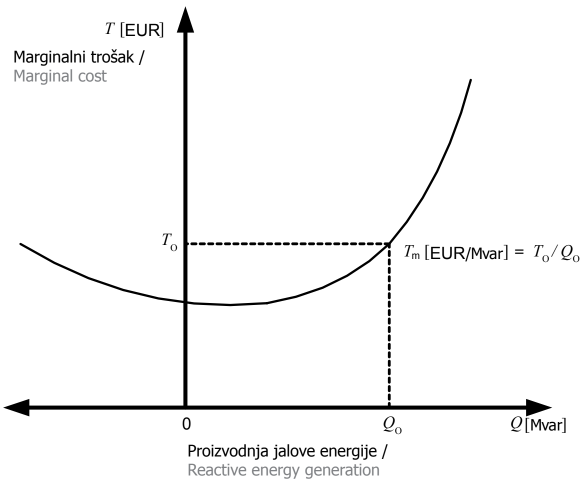
a, b – koeficijenti pravca koji aproksimira krivulju pogonskog dijagama generatora,
$P_{\mathrm{G}i\mathrm{S}}$ – zadana proizvodnja djelatne snage u čvorištu i (slika 1),
$Q_{\mathrm{G}i\mathrm{S}}$ – maksimalna proizvodnja jalove snage u čvorištu i s obzirom na zadanu proizvodnju djelatne snage u čvorištu i (slika 1),
$P'_{\mathrm{G}i\mathrm{S}}$ – smanjena vrijednost proizvodnje djelatne snage u čvorištu i,
$P_{\mathrm{G}i\min}$ – tehnički minimum sinkronog generatora u čvorištu i,
$Q_{\mathrm{G}i\max}$ – ograničenje proizvodnje jalove snage u čvorištu i (slika 1).

Temeljem proračunatih optimalnih vrijednosti proizvodnje jalove snage sinkronih generatora za svaku se naponsku zonu provodi zasebni dražbeni postupak. Najviši marginalni trošak određuje cijenu jalove snage u svakoj od zona, slika 5, gdje je Q_{o} proračunata optimalna vrijednosti proizvodnje jalove snage, T_{o} odgovarajući trošak i T_{m} odgovarajući marginalni trošak.

where:

a, b – line coefficients approximating the generator's operating diagram curve,
$P_{\mathrm{G}i\mathrm{S}}$ – given active power generation in node i (Figure 1),
$Q_{\mathrm{G}i\mathrm{S}}$ – maximal reactive power generation in node i relative to given active power generation in node i (Figure 1),
$P'_{\mathrm{G}i\mathrm{S}}$ – reduced value of active power generation in node i,
$P_{\mathrm{G}i\min}$ – the synchronous generator's technical minimum in node i,
$Q_{\mathrm{G}i\max}$ – reactive power generation limitation in node i (Figure 1).

Based on the calculated optimal values of reactive power generated by synchronous generators, a separate auction procedure is conducted for every voltage zone. The highest marginal cost determines the price of reactive power in each zone, Figure 5, where Q_{o} is the calculated optimal value of reactive power generation, T_{o} is the corresponding cost, and T_{m} is the corresponding marginal cost.



Slika 5 — Određivanje marginalnog troška proizvodnje jalove snage
Figure 5 – Determining the marginal cost of reactive power generation

U drugom koraku predloženi optimizacijski algoritam uzima u obzir različita sigurnosna ograničenja, pri čemu je potrebno odlučiti se između dva ekonomska kriterija i posljedicama koje proizlaze iz njihovog zadovoljenja:

- minimiziranje gubitaka u mreži ima za posljedicu više vrijednosti napona u čvorištima mreže te maksimiziranje prijenosne moći, no i veće troškove proizvodnje jalove snage te smanjenje pričuve jalove snage u sinkronim generatorima. Dodatno, moguć je učestali angažman vrlo skupe elektrane bliske centru potrošnje,
- minimiziranje proizvodnje jalove snage posredno donosi sljedeće pozitivne i negativne učinke: niže vrijednosti napona u čvorištima mreže i veće gubitke u mreži, no i veću pričuvu jalove snage u sinkronim generatorima. Pri tome postoji opasnost od angažiranja jeftinih, ali udaljenih elektrana što dodatno narušava uvjete u mreži. No, za očekivati je da se zonskim pristupom donekle izbjegavaju spomenute negativne posljedice budući da je izbor generatora ograničen na usko područje – naponsku zonu.

Da bi se istodobno zadovoljila oba navedena kriterija i time minimizirali ukupni pogonski troškovi funkcija cilja se može izraziti kao zbroj ukupnih gubitaka u mreži i ukupno proizvedene jalove snage:

The optimization algorithm proposed in the second step takes into account various safety limitations, where one should choose between two economic criteria and the consequences resulting from meeting them:

- the minimization of network losses results in higher voltage values in network nodes and in the maximization of transmission capability, as well as higher costs of reactive power generation and a reduced reactive power reserve in the synchronous generators. What is also possible is a repeated engagement of a very expensive power plant near the consumption center,
- the minimization of reactive power generation indirectly has the following positive and negative effects: lower voltage values in network nodes and higher network losses, but also a higher reactive power reserve in the synchronous generators. This harbors a risk of engaging cheap but remote power plants, which additionally disrupts the network conditions. It is to be expected, however, that with the zonal approach the mentioned negative effects will be avoided, because the choice of generators is confined to a narrow area – the voltage zone.

In order to meet both criteria simultaneously and thereby minimize the total operating costs, the goal function can be expressed as a sum of total network losses and total reactive power generated:

$$F(x,u) = P_{\mathrm{GUB}} + Q_{\mathrm{Guk}} = \frac{1}{2}\sum_{i}^{n}\sum_{j}^{n} G_{ij}\left[U_i^2 + U_j^2 - 2U_iU_j\cos\left(\delta_i - \delta_j\right)\right] + \sum_{k}^{Ng} Q_{\mathrm{g}k} \quad , \qquad (13)$$

gdje su:

P_{GUB} – gubici djelatne snage u prijenosnoj mreži,
Q_{Guk} – ukupna proizvodnja jalove snage generatora,
Q_{gk} – proizvodnja jalove snage $k-\mathrm{og}$ generatora,
N_{g} – ukupan broj generatora i
n – broj čvorišta mreže.

Izraz (13) sadrži dva kriterija, te na taj način predstavlja problem višekriterijskog optimiranja. Višekriterijsko optimiranje vrlo je čest problem u različitim područjima primjene, od ekonomije do ekologije ili strojarskog inženjerstva. Višekriterijsko optimiranje je najčešće zasnovano na Pareto skupu optimalnih rješenja, i vrlo je korisno u procesu planiranja, dizajna te razvoja zbog sistematičnog pristupa. Pareto skup predstavlja skup svih ili većine mogućih optimalnih rješenja. Takav skup od desetak do ponekad stotinu i više optimalnih rješenja potrebno je zatim dodatno analizirati i nekom od razvijenih metoda odlučivanja izabrati najprikladnije [16].

Budući da problem koji se obrađuje u članku obuhvaća vremenski opseg kratkoročnog planiranja pogona EES-a, tj. izrade optimalnog naponskog plana za dan ili sat unaprijed, predloženi algoritam optimiranja mora biti jednoznačan. Moguće je samo jedno rješenje, tj. samo jedan optimalni naponski plan, za promatrano vremensko razdoblje. Stoga ovdje nije prikladno primijeniti višekriterijsko optimiranje zasnovano na Pareto skupu optimalnih rješenja, odnosno bilo kojoj drugoj metodologiji s vrednovanjem većeg broja optimalnih rješenja.

Jedno optimalno rješenje višekriterijskog optimizacijskog problema moguće je dobiti odabirom odgovarajućih težinskih faktora kojima se množe suprotstavljeni kriteriji. Na taj se način kriteriji vrednuju, odnosno izravno se odlučuje o redoslijedu važnosti kriterija, što u konačnici dovodi do željenog rješenja. Da bi se izraz koji predstavlja djelatnu ili jalovu energiju pretvorio u izraz za financijske troškove, potrebno ga je pomnožiti s jediničnom cijenom djelatne ili jalove energiju.

Množeći izraz za gubitke u mreži s jediničnom cijenom djelatne energije i ukupnu proizvodnju jalove snage svake naponske zone s odgovarajućom jediničnom cijenom jalove energije, određenom dražbenim postupkom na temelju prvog optimizacijskog koraka, izraz za funkciju cilja iz (13) pretvara se u istodobnu minimizaciju troškova nabave energije za pokriće gubitaka u mreži i troškova plaćanja za proizvedenu jalovu energiju u sklopu pružanja pomoćne usluge regulacije napona i jalove snage:

where:

P_{GUB} – active power losses in the transmission network,
Q_{Guk} – the generator's total reactive power output,
Q_{gk} – reactive power generation by the $k-\mathrm{th}$ generator,
N_{g} – total number of generators, and
n – number of network nodes.

Expression (13) contains two criteria and thus poses a problem of multi-criterion optimization. The multi-criterion optimization is a problem very often occurring in various areas of application, from economics to ecology or mechanical engineering. The multi-criterion optimization is mostly based on the Pareto set of optimal solutions, and, owing to its systematic approach, is highly useful in the process of planning, designing and development. The Pareto set is a set of all or most possible optimal solutions. Such a set of about ten or up to one hundred or more optimal solutions should then be additionally analyzed and the most suitable ones amongst them should be chosen by using one of the advanced decision-making methods [16].

Since the problem addresed in the present article comprises the time range of the short-term planning of EPS operation, i.e., preparing of the optimal voltage plan for a day or an hour in advance, the proposed optimization algorithm must be unequivocal. In other words, there is room for only one solution, i.e., only one optimal voltage plan for the observed period. Therefore, it is not suitable here to apply the multi-criterion optimization based on the Pareto set of optimal solutions, or for that matter on any other methodology involving the evaluation of a greater number of optimal solutions.

One optimal solution to a multi-criterion optimization problem can be obtained by selecting appropriate weight factors with which the opposed criteria are multiplied. In this way the criteria are evaluated and it is thus directly decided on their order of priority, which in the end leads to the desired solution. For the expression representing active or reactive energy to be transformed into the expression representing financial costs, it should be multiplied with the unit price of active or reactive energy.

By multiplying the expression for network losses with the unit price of active energy and the total reactive power generation of each voltage zone with the corresponding unit price of reactive energy, set through an auction procedure based on the first optimization step, the goal function expression (13) is transformed into the simultaneous minimization of energy procurement costs for the coverage of network losses and the costs of payment for generated reactive energy within the provision of the voltage and reactive power control support service:

$$F(x,u) = c_{\mathrm{GUB}} \cdot P_{\mathrm{GUB}} + \sum_{z=1}^{N_z} c_{\mathrm{Qz}} \cdot \sum_{k}^{N_{gz}} Q_{\mathrm{Gk}} \tag{14}$$

gdje je:

c_{GUB} – cijena djelatne energije za pokriće gubitaka u mreži [EUR/MW], a
c_{Qz} – jedinstvena cijena jalove energije u naponskoj zoni z [EUR/Mvar].

Konačni izraz za funkciju cilja može se dodatno pojednostaviti kao suma ukupnih financijskih troškova:

$$T = T_{\mathrm{GUB}} + T_{\mathrm{Q}} \,, \tag{15}$$

gdje je:

T – ukupan financijski trošak [EUR],
T_{GUB} – financijski trošak nabave djelatne energije za pokriće gubitaka u mreži [EUR] i
T_{Q} – financijski trošak proizvedene jalove energije [EUR] u sklopu pružanja pomoćne usluge regulacije napona i jalove snage.

Troškovi se minimiziraju s obzirom na sljedeća ograničenja tipa jednakosti i ograničenja tipa nejednakosti:

- jednadžbe tokova snaga (6), (7),
- ograničenja proizvodnje jalove snage (8),
- ograničenja vrijednosti napona u čvorištima (9),
- ograničenja položaja preklopki transformatora (10),
- ograničenja vrijednost tokova prividne snage na elementima mreže (11).

Izlazne varijable drugog optimizacijskog koraka su optimalni položaji preklopki transformatora s mogućnošću promjene prijenosnog omjera pod opterećenjem, optimalni položaji mrežnih kompenzacijskih uređaja te optimalne postavne vrijednosti automatskih regulatora napona sinkronih generatora. Sve navedene vrijednosti zajedno predstavljaju optimalan naponski plan za određeno vremensko razdoblje. Prije konačnog prihvaćanja optimalnog naponskog plana potrebno je provjeriti jesu li zadovoljena sigurnosna ograničenja ($n-1$ analiza).

where:

c_{GUB} – the price of active energy for the coverage of network losses [EUR/MW], and
c_{Qz} – the uniform price of reactive energy in a voltage zone z [EUR/Mvar].

The final expression for the goal function can be further simplified as a sum of total financial costs:

where:

T – total financial cost [EUR],
T_{GUB} – financial cost of active energy procurement for the coverage of network losses [EUR], and
T_{Q} – financial cost of generated reactive energy [EUR] within the provision of the voltage and reactive power control support service.

The costs are minimized relative to the following equality-type and inequality-type limitations:

- power flow equations (6), (7),
- limitations on reactive power generation (8),
- limitations on voltage values in nodes (9),
- limitations on the positions of transformer switchgears (10),
- limitations on the values of apparent power flows on network elements (11).

The output variables of the second optimization step are optimal positions of transformer switchgears, with a possibility of changing the transmission ratio under load, optimal positions of network reactive compensation devices, and optimal set values of automatic voltage controls of the synchronous generators. All these value together make an optimal voltage plan for a certain period of time. Prior to final acceptance of the optimal voltage plan it should be checked if the safety limitation requirements are met ($n-1$ analysis).

4 REZULTATI TESTIRANJA NA MODELU HRVATSKOG EES-a

4.1 Podjela hrvatskog EES-a u naponske zone

Predložena metodologija vrednovanja pomoćne usluge $U-Q$ regulacije provjerena je na primjeru stvarnog EES-a, na scenarijima ostvarenima u naravi, kako bi se na taj način stekao uvid u mogućnosti primjene predložene metodologije u praksi. Izabran je model hrvatskog EES-a, s pretpostavkom korištenja metodologije od strane hrvatskog OPS-a. Modelirani su svi elementi naponske razine 400 kV i 220 kV, te gotovo čitava mreža 110 kV. Manji dio radijalno spojenih čvorišta i pripadnih vodova nije modeliran. Svi mrežni transformatori modelirani su kao dvonamotni, uz uvažavanje stvarnog regulacijskog opsega transformatora s mogućnošću regulacije iznosa napona pod opterećenjem. Vanjska rubna čvorišta hrvatskog EES-a modelirana su kao $P-Q$ injekcije.

Međusobne električne udaljenosti čvorišta hrvatskog EES-a proračunate su za puno uklopno stanje mreže, tj. sa svim elementima mreže (vodovi, kabeli, transformatori) u pogonu. Korištenjem metode električnih udaljenosti određene su glavne generatorske grupe, kao osnova za određivanje naponskih zona. Analizom izračunatih električnih udaljenosti među generatorima hrvatskog EES-a određene su tri generatorske grupe. Time je postavljen računski temelj za podjelu hrvatskog EES-a u tri naponske zone. Zatim su korištenjem metode električnih udaljenosti određena granična čvorišta naponskih zona te su naponske zone time u potpunosti određene, slika 6.

Prva naponska zona (zona Sjever) sadrži ukupno 64 čvorišta, od toga 10 generatorskih. Druga naponska zona (zona Zapad) sadrži ukupno 36 čvorišta, od toga 9 generatorskih, dok treća naponska zona (zona Jug) sadrži ukupno 32 čvorišta, od toga 9 generatorskih. Određena su sljedeća granična čvorišta naponskih zona:

- Zone Sjever i Zapad: Tumbri 400 kV, Mraclin 220 kV, Tumbri 110 kV, Rakitje 110 kV (Sjever) i Melina 400 kV, Brinje 220 kV, Švarča 110 kV, Zdenčina 110 kV (Zapad),
- Zone Zapad i Jug: Melina 400 kV, Brinje 220 kV, Gračac 110 kV, Pag 110 kV, (Zapad) i Velebit 400 kV, Konjsko 220 kV, Obrovac 110 kV, Nin 110 kV (Jug),
- Zone Sjever i Jug nemaju graničnih čvorišta odnosno zajedničkih vodova.

4 RESULTS OF TESTING ON THE MODEL OF THE CROATIAN EPS

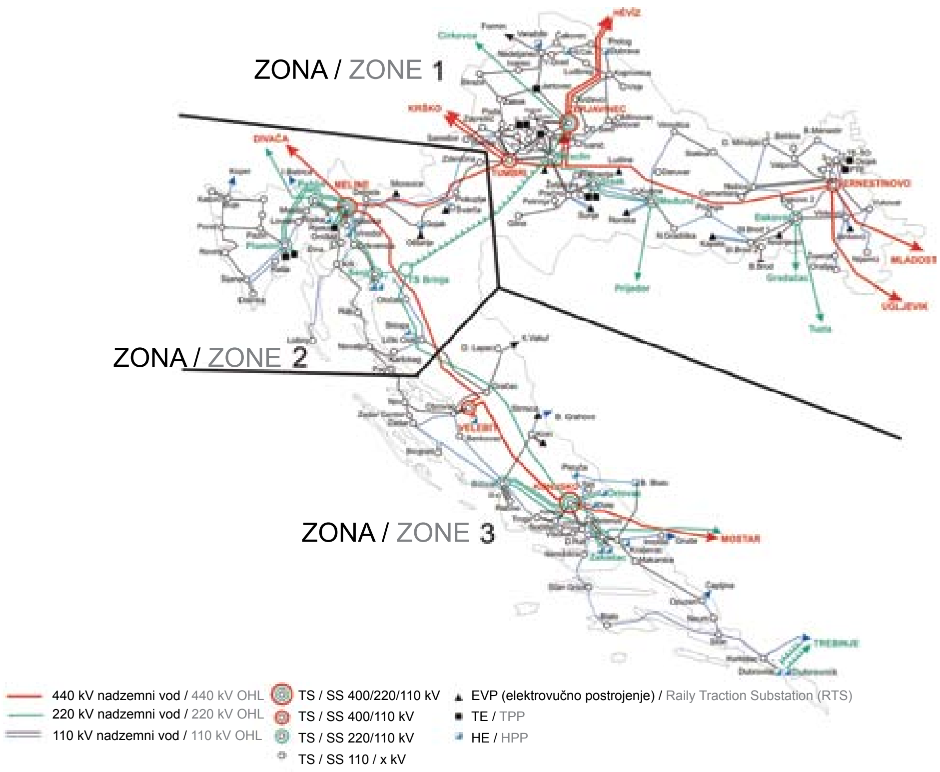
4.1 Division of the Croatian EPS into voltage zones

The proposed methodology of assessing the voltage control ancillary services has been checked on the example of a real EPS, on scenarios implemented in reality, in order to gain an insight into the applicability of the proposed methodology in practice. The model of the Croatian EPS was chosen with a view to having the methodology used by the Croatian EPS. All elements of 400 kV and 220 kV voltage levels and nearly the whole 110 kV network have been modeled. A minor part of radially connected nodes has not been modeled. All network transformers have been modeled as two-winding transformers, with allowance being made for the real control range of the transformers including the possibility of controlling the amount of voltage under load. The external fringe nodes of the Croatian EPS have been modeled as $P-Q$ injections.

Mutual electrical distances of the Croatian EPS's nodes have been calculated for full on-state of the network, i.e., with all network elements (lines, cables, transformers) in operation. By using the electrical distance method the main generator groups have been defined as a basis for defining the voltage zones. Three generator groups have been defined by analyzing the computed electrical distances between the generators of the Croatian EPS. Thus a computation basis has been laid for the division of the Croatian EPS into three voltage zones. Then, by using the electrical distance method, the boundary nodes of the voltage zones have been wholly defined, Figure 6.

The first voltage zone (zone North) contains a total of 64 nodes, of which 10 generator nodes. The second voltage zone (zone West) contains a total of 36 nodes, of which 9 generator zones, whereas the third voltage zone (zone South) contains a total of 32 nodes, of which 9 generator nodes. The following boundary nodes of the voltage zones have been defined:

- Zones North and West: Tumbri 400 kV, Mraclin 220 kV, Tumbri 110 kV, Rakitje 110 kV (North) and Melina 400 kV, Brinje 220 kV, Švarča 110 kV, Zdenčina 110 kV (West),
- Zones West and South: Melina 400 kV, Brinje 220 kV, Gračac 110 kV, Pag 110 kV, (West) and Velebit 400 kV, Konjsko 220 kV, Obrovac 110 kV, Nin 110 kV (South),
- Zones North and South have no boundary nodes, or shared lines.



Slika 6 – Shema hrvatskog EES-a s određenim naponskim zonama, pri punom uklopnom stanju mreže
Figure 6 – Outline of the Croatian EPS with defined voltage zones at full on-state of the network

U tablici 1 predočena je pripadnost generatorskih čvorišta naponskim zonama.

Table 1 shows the classification of the generator nodes under the respective voltage zones.

Tablica 1 – Pripadnost generatorskih čvorišta naponskim zonama
Table 1 – Generator nodes matched with voltage zones

Generatori / Generators		
Zona Sjever / Zone North	Zona Zapad / Zone West	Zona Jug / Zone South
EL-TO / CHP EL-TO 110 kV	HE / HPP Rijeka 110 kV	HE / HPP Dubrovnik 110 kV
HE / HPP Čakovec 110 kV	HE / HPP Gojak 110 kV	HE / HPP Kraljevac 110 kV
HE / HPP Dubrava 110 kV	HE / HPP Senj 220 kV	HE / HPP Orlovac 220 kV
HE / HPP Varaždin 110 kV	HE / HPP Senj 110 kV	HE/ HPP Peruća 110 kV
TE-TO / CHP 1 110 kV	HE / HPP Vinodol 110 kV	HE / HPP Zakučac 220 kV
TE-TO / CHP 2 110 kV	HE / HPP Sklope 110 kV	HE / HPP Zakučac 110 kV
TE / TPP Jertovec 110 kV	TE / TPP Plomin 220 kV	HE / HPP Đale 110 kV
TE / TPP Sisak 220 kV	TE / TPP Plomin 110 kV	RHE / PSHPP Velebit 400 kV
TE / TPP Sisak 110 kV	TE / TPP Rijeka 220 kV	HE / HPP Kraljevac 110 kV
PTE / TPP Osijek 110 kV		

Proračun električnih udaljenosti hrvatskog EES-a donio je i neke općenite zaključke. Na 110 kV razini pripadnost naponskoj zoni jasno je razlučena, a potrošačka čvorišta koncentrirana oko proizvod-

The electrical distance calculation for the Croatian EPS has also led to some general conclusions. At 110 kV level the classification under a voltage zone is clearly defined, whereas the consumer nodes nih čvorišta. Na višim naponskim razinama geografski udaljena čvorišta električki su bliska jedna drugima, a granice između naponskih zona nisu tako čvrste i jasno određene. Tako je RHE Velebit, priključena u 400 kV čvorištu Velebit, preko 400 kV poteza od čvorišta Konjsko preko čvorišta Melina do čvorišta Tumbri, pa i dalje prema čvorištu Ernestinovo, bliža određenim čvorištima u drugim zonama nego elektrane koje su i geografski i električki smještene u tim zonama no priključene na nižem naponu. HE Senj i TE Sisak su, zbog svog električkog položaja, preko 220 kV vodova električki vrlo bliski čvorištima drugih zona.

Međusobne utjecaje naponskih zona, pogotovo u izrazito uzamčenoj električnoj mreži, nemoguće je izbjeći, no oni ne utječu značajnije na naponske prilike niti na raspodjelu proizvodnje jalove snage unutar naponskih zona. Ukoliko bi se takve pojave uočile u praktičnoj primjeni ove ili slične metodologije, bilo bi potrebno redefinirati granice naponskih zona, a po potrebi provesti okrupnjivanje dvije ili više naponskih zona u jednu.

4. 2 Utjecaj uklopnog stanja mreže na granice naponskih zona hrvatskog EES-a

U sklopu istraživanja utjecaja uklopnog stanja mreže na granice naponskih zona, na primjeru hrvatskog EES-a, obrađeno je ukupno devet isklopa za koje je pretpostavljeno da bi mogli imati najveći utjecaj na promjene granica naponskih zona, od toga četiri isklopa u 400 kV mreži , tri isklopa u 220 kV mreži i dva isklopa u 110 kV mreži:

1. Isklop DV 400 kV Melina –Tumbri: ne mijenja se struktura generatorskih grupa, niti se mijenjaju granice zona. 400 kV čvorište Tumbri je pod znatno manjim utjecajem ostalih zona, dok su za ostala granična čvorišta promjene minimalne. Općenito je slabiji utjecaj generatora zone Zapad na čvorišta zone Sjever i obrnuto.
2. Isklop DV 400 kV Tumbri – Žerjavinec: ne mijenja se struktura generatorskih grupa, niti se mijenjaju granice zona. 400 kV čvorište Tumbri pod neznatno je većim utjecajem ostalih zona, dok su za ostala granična čvorišta promjene minimalne. Primjetan je jači utjecaj generatora zone Zapad na čvorišta zone Sjever oko TS 400 kV Tumbri.
3. Isklop DV 400 kV Melina – Velebit: ne mijenja se struktura generatorskih grupa, niti se mijenjaju granice zona. Manji je utjecaj 400 kV čvorišta Velebit na čvorišta zona Sjever i Zapad, TS 400 kV Melina i Velebit

are concentrated around the generation nodes. At higher voltage levels the geographically distant nodes are electrically close to one another and the boundaries between the voltage zones are not so firmly and clearly defined. Thus the PSHPP Velebit, connected in the 400 kV Velebit node, over the 400 kV stretch from the Konjsko node through the Melina node to the Tumbri node, and even further on towards the Ernestinovo node, is closer to some nodes in other zones than the power plants which are both geographically and electrically situated in these zones, but connected at a lower voltage. HPP Senj and TPP Sisak are via 220 kV lines, electrically very close to the nodes of other zones, owing to their electrical position.

The mutual influences of voltage zones, especially in a markedly interconnected electrical network, are impossible to avoid, but their impact on voltage conditions or on the distribution of reactive power generation within the voltage zones is not significant. Should such occurrences be detected in the practical application of this or similar methodology, the boundaries of the voltage zones would have to be redefined and, if required, two or more voltage zones merged into one.

4.2 The impact of the network's on-state on the boundaries of the Croatian EPS's voltage zones

The study of the impact of the network's on-state on the boundaries of the voltage zones on the example of the Croatian EPS encompasses a total of nine disconnections that may presumably have the greatest influence on the changes in the boundaries of the voltage zones, including four disconnections in the 400 kV network, three disconnections in the 220 kV network and two disconnection in the 110 kV network:

1. Disconnection of TL (Transmission Line) 400 kV Melina –Tumbri: no change in the structure of generator groups, and no change in the zonal boundaries. The 400 kV Tumbri node is much less influenced by other zones, whereas changes for other boundary nodes are minimal. Generally, the influence of the generators of zone West on the nodes of zone North is weaker than the other way around.
2. Disconnection of TL 400 kV Tumbri – Žerjavinec: no change in the structure of generator groups, and no change in the zonal boundaries. The 400 kV Tumbri node is slightly more influenced by other zones, whereas changes for other boundary nodes are minimal. What is noticeable is a stronger influence of the zone West generators on the zone North nodes around the SS 400 kV Tumbri.
3. Disconnection of TL 400 kV Melina – Velebit: no change in the structure of generator groups, and no change in the zonal boundaries. There is

više nisu granična čvorišta, dok su za ostala granična čvorišta promjene minimalne.

4. Isklop DV 400 kV Konjsko – Velebit: značajna promjena granice između zona Zapad i Jug. 400 kV čvorište Velebit pripaja se generatorskoj grupi zone Zapad, a sva rubna čvorišta iz zone Jug pripajaju se zoni Zapad. Granica zona Zapad i Jug postaje čvršća, zbog manjeg utjecaja susjednih zona na granična čvorišta, te se pomiče prema jugu.
5. Isklop DV 220 kV Brinje – Mraclin: ne mijenja se struktura generatorskih grupa, niti se mijenjaju granice zona. Granica zona Sjever i Zapad postaje čvršća, zbog manjeg utjecaja susjednih zona na granična čvorišta, a TS 220 kV Mraclin više nije granično čvorište.
6. Isklop DV 220 kV Brinje – HE Senj: TS 220 kV Brinje potpada pod jak utjecaj generatorskog čvorišta TE Sisak i pripaja se zoni Sjever, no ujedno postaje rubno čvorište zona Sjever i Jug zbog značajnog utjecaja generatorskih čvorišta HE Zakučac i HE Orlovac. Ne mijenja se struktura generatorskih grupa, a promjene za ostala granična čvorišta su minimalne.
7. Isklop DV 220 kV Brinje – Konjsko: ne mijenja se struktura generatorskih grupa, niti se mijenjaju granice zona. TS 220 kV Brinje više nije granično čvorište zona Zapad i Jug, a promjene za ostala granična čvorišta zona Zapad i Jug su minimalne.
8. Isklop DV 110 kV HE Gojak – HE Vinodol: HE Gojak pripaja se generatorskoj grupi zone Sjever, kao i oba 110 kV čvorišta na potezu od HE Gojak do 110 kV čvorišta Tumbri (Pokuplje, Zdenčina). Granična čvorišta zona Sjever i Zapad ostaju TS 220 kV Brinje i
9. TS 110 kV Švarča, oba ostaju u sastavu zone Zapad. Osim HE Gojak, ne mijenja se pripadnost ostalih generatorskih čvorišta, a promjene za ostala granična čvorišta između triju zona su minimalne.
10. Isklop DV 110 kV HE Senj – Otočac: Iako HE Sklope električki postaje najbliže generatorskom čvorištu 400 kV Velebit iz zone Jug, odmah iza slijede generatorska čvorišta zone Zapad: HE Vinodol, HE Senj i HE Rijeka. Stoga je opravdano zadržati ovo čvorište u sklopu generatorske grupe zone Zapad, a time i okolna 110 kV čvorišta Otočac, Novalja i Pag. Granica zona Zapad i Jug pomiče se na sjever na način da TS 110 kV Gračac ulazi u sastav zone Jug.

Uklopno stanje mreže utječe donekle na granice naponskih zona, a rjeđe i na pripadnost određene elektrane nekoj zoni, no to ne predstavlja problem u izvedbi predložene

a minor influence of the 400 kV Velebit node on the nodes of zones North and West, SS 400 kV Melina and Velebit are no longer boundary nodes, whereas changes for other boundary nodes are minimal.

4. Disconnection of TL 400 kV Konjsko – Velebit: a significant change in the boundary between zone West and zone South. The 400 kV Velebit node is attached to the generator group of zone West, and all boundary nodes from zone South are attached to zone West. The West-South boundary becomes firmer, due to a smaller influence of the adjacent zones on the boundary nodes, and is shifted to the south.
5. Disconnection of TL 220 kV Brinje – Mraclin: no change in the structure of generator groups, and no change in the zonal boundaries. The North-West boundary becomes firmer, due to a smaller influence of the adjacent zones on the boundary nodes, and the SS 220 kV Mraclin is no longer a boundary node.
6. Disconnection of TL 220 kV Brinje – HPP Senj: The SS 220 kV Brinje is strongly influenced by the generator node TPP Sisak and is attached to zone North, but at the same time becomes a boundary node of zones North and South due to a significant influence of the generator nodes of HPP Zakučac and HPP Orlovac. No change in the structure of generator groups, and no change in the zonal boundaries.
7. Disconnection of TL 220 kV Brinje – Konjsko: no change in the structure of generator groups, and no change in the zonal boundaries. The SS 220 kV Brinje is no longer a boundary node of zones West and South, whereas changes for other boundary nodes of zones West and South are minimal.
8. Disconnection of TL 110 kV HPP Gojak – HPP Vinodol: HPP Gojak is attached to the generator group of zone North, as are both 110 kV nodes in the stretch from HPP Gojak to 110 kV node Tumbri (Pokuplje, Zdenčina). The boundary nodes of zones North and West remain SS 220 kV Brinje and SS 110 Švarća, both within zone West. Except for the HPP Gojak, no changes in the classification of other generator nodes, whereas changes for other boundary nodes in between three zones are minimal.
9. TS 110 kV Švarča, both remain within zone West. Except for HPP Gojak, the classification of other generator nodes remains unchanged, whereas changes for other boundary nodes between the three zones are minimal.
10. Disconnection of TL 110 kV HPP Senj – Otočac: Although the HPP Sklope electrically becomes closest to the generator node of 400 kV Velebit from zone South, what follows right after are the generator nodes of zone West: HPP Vinodol, HPP Senj and HPP Rijeka. It is hence justified to keep these zones within the generator group of zone West, and thereby also the surrounding 110

metodologije budući da se radi o statičkim proračunima u fazi kratkoročnog planiranja, dakle izvan stvarnog vremena. Zaključak je da je metoda podjele EES-a u naponske zone prema kriteriju električnih udaljenosti u potpunosti primjenjiva na statičke proračune, za razliku od primjenjivosti iste s obzirom na zahtjeve automatske sekundarne $U-Q$ regulacije, gdje dinamičke promjene u stvarnom vremenu zahtijevaju primjenu kompleksnijih metoda s dinamički promjenjivim granicama.

4.3 Rezultati ispitivanja optimizacijskog algoritma na modelu hrvatskog EES-a

Razvijeni optimizacijski algoritam ispitan je na prethodno opisanom modelu hrvatskog EES-a za scenarij maksimalnog opterećenja, koji je određen na temelju podataka o opterećenjima čvorišta mreže i proizvodnji elektrana za stanje ostvareno u prosincu 2007. godine. Ukupno opterećenje hrvatskog EES-a, uključujući i gubitke prijenosa, iznosi 2 983 MW, a ukupna proizvodnja agregata u sastavu hrvatskog EES-a 2 528 MW. Bilanca snage hrvatskog EES-a uravnotežena je uvozom ostatka snage iz susjednih elektroenergetskih sustava. Modelirana razmjena elektroenergetskog sustava Hrvatske sa susjednim sustavima ne odnosi se samo na planiranu razmjenu dvaju sustava već uvažava i tzv. neplanirane tokove koji se zatvaraju preko hrvatskog EES-a kao posljedica uzamčene visokonaponske mreže UCTE-a (engl. Union for Coordination of Transmission of Electricity).

Određivanje krivulje troškova proizvodnje jalove snage stvarnih generatorskih jedinica predstavlja poseban problem budući da se procjena gubitaka u stroju najčešće određuje mjerenjem, putem različitih metoda, a rjeđe i putem složenih proračuna. Za generatore u hrvatskom EES-u takvi su podaci bili nedostupni, te je za određivanje krivulja troškova proizvodnje jalove snage generatora u hrvatskom EES-u korištena dostupna literatura [17], na temelju koje je približno određena ovisnost gubitaka djelatne snage generatora o promjeni uzbudne struje, tj. proizvodnji jalove snage tog generatora. Tablica 2 daje osnovne podatke o regulacijskom opsegu elektrana s obzirom na postavljeni iznos proizvodnje djelatne snage te koeficijente krivulje troškova proizvodnje jalove snage svih raspoloživih izvora jalove snage korištenog modela hrvatskog EES-a. Aproksimirane krivulje troškova su kvadratnog oblika, s koeficijentima c_0, c_1 i c_2.

kV nodes of Otočac, Novalja and Pag. The boundary between zones West and South is shifted to the north so that the SS 110 kV Gračac becomes a part of zone South.

The on-state of the network exerts a certain influence on the voltage zone boundaries, and less often so on the classification of a power plant under a particular zone, but that poses no problem in the implementation of the proposed methodology, because it is a case of static calculations in the short-term planning stage, outside the real time. Conclusion: the method of dividing the EPS into voltage zones according to the criterion of electrical distances is wholly applicable to static calculations, unlike its applicability in respect of the requirements of the automatic secondary U-Q control, where the dynamic real-time changes require the application of more complex methods with dynamically changeable boundaries.

4.3 Results of testing the optimization algorithm on the Croatian EPS model

The developed optimization has been tested on the above described Croatian EPS model for a maximum load scenario defined on the basis of load data on the network nodes and the output of power plants for the status of December 2007. The total load of the Croatian EPS, including transmission losses, is 2 983 MW, and the total output of generator units within the Croatian EPS is 2 528 MW. The power balance of the Croatian EPS is achieved through the import of the rest of required power from the neighboring electric power systems. The modeled exchange between the Croatian electric power system and the neighboring systems is not confined to the planned exchange of two systems, it also makes allowance for the so-called unplanned flows which are being closed over the Croatian EPS as a result of the interconnected high-voltage network of UCTE (Union for Coordination of Transmission of Electricity).

The definition of the cost curve of reactive power generation by real generator units poses a special problem, since the assessment of losses in the machine is mostly made by measurement using various methods, and less often by means of complex calculations. For the generators in the Croatian EPS such data were inaccessible, so accessible literature [17] was used in the definition of the cost curve of reactive power generation by the generators in the Croatian EPS, based on which the dependence of a generator's active power losses on the changes in excitation current, i.e., on the reactive power generation by that generator, was approximately determined. Table 2 gives basic data on the control range of power plants relative to the set active power output and the coefficients of the costs curves of reactive power generation from all available reactive power sources of the used model of the Croatian EPS. The approximated cost curves are square-shaped, with coefficients c_0, $c_1$and c_2.

Tablica 2 –Proizvodnja djelatne snage, regulacijski opseg i koeficijenti krivulje troškova proizvodnje jalove snage sinkronih generatora i kompenzacijskih uređaja hrvatskog EES-a

Table 2 – Active power generation, control range and coefficients of the cost curves of reactive power generation by the synchronous generators and reactive compensation devices of the Croatian EPS

Čvorište / Node	P_S [MW]	Q_{max} [Mvar]	Q_{min} [Mvar]	c_2 [EUR/Mvar^2]	c_1 [EUR/Mvar]	c_0 [EUR]
EL-TO / CHP EL-TO 110 kV	50	40	–20	0,026 3	–0,089 0	0
HE / HPP Čakovec 110 kV	80	25	–15	0,018 0	–0,017 5	0
HE / TPP Dubrava 110 kV	80	25	–15	0,018 0	–0,017 5	0
HE / TPP Varaždin 110 kV	80	60	–27,4	0,016 0	–0,066 2	0
NE / NPP Krško 400 kV	670	150	–100	0,012 5	–0,001 5	0
PTE / TPP Osijek 110 kV	20	38	–25	0,025 8	–0,080 7	0
TE-TO / CHP 1 110 kV	140	45	–40	0,022 9	–0,080 4	0
TE-TO / CHP 2 110 kV	180	120	–45	0,022 5	–0,118 0	0
TE / TPP Sisak 220 kV	200	135	-46	0,020 1	–0,073 1	0
TE / TPP Sisak 110 kV	200	140	-22	0,020 3	–0,038 7	0
HE / HPP Senj 220 kV	70	35,1	–36,1	0,016 1	–0,019 9	0
HE / HPP Senj 110 kV	140	70,2	–72,2	0,016 1	0,019 9	0
HE / HPP Vinodol 110 kV	60	62,4	–10,8	0,014 4	0,007 7	0
HE / HPP Sklope 110 kV	20	10,4	–13,9	0,016 4	0,028 4	0
TE / TPP Plomin 220 kV	190	110	–30	0,023 1	–0,165 0	0
TE / TPP Plomin 110 kV	105	48	0	0,043 7	–0,364 0	0
TE / TPP Rijeka 220 kV	300	180	–117	0,020 2	–0,067 9	0
HE / HPP Dubrovnik 110 kV	105	70	–73	0,018 5	0,032 0	0
HE / HPP Orlovac 220 kV	70	29	–26	0,016 2	–0,033 0	0
HE / HPP Peruća 110 kV	40	30,8	–22,4	0,016 4	–0,046 5	0
HE / HPP Zakučac 220 kV	135	67	–55	0,016 2	0,005 8	0
HE / HPP Zakučac 110 kV	108	69	–73	0,016 2	0,017 4	0
HE / HPP Đale 110 kV	20	13	–16	0,016 4	0,014 9	0
RHE / PSHPP Velebit 400 kV	135	50	–67	0,015 7	–0,013 3	0
KB / CB Đakovo 110 kV	–	48	0	0	0,050 0	0
PR / Ind. Ernestinovo 110 kV	–	0	–100	0	0,050 0	0

U generatorsku grupu naponske zone Sjever uključen je i hrvatski dio NE Krško, tj. pretpostavljeno je da hrvatski OPS upravlja polovicom regulacijskog opsega elektrane te da elektrana stoga ravnopravno sudjeluje u davanju ponuda za proizvodnju jalove snage u ograničenom opsegu. Od raspoloživih mrežnih kompenzacijskih uređaja instaliranih u hrvatskom EES-u modelirana je prigušnica snage 100 Mvar, instalirana u TS Ernestinovo, i kondenzatorska baterija snage 3x16 Mvar, instalirana u TS Đakovo. Oba uređaja smještena su unutar naponske zone Sjever. Troškovi proizvodnje jalove snage mrežnih kompenzacijskih uređaja pretpostavljeni su kao fiksni, s vrijednošću od 0,05 EUR/Mvar.

Predloženi optimizacijski algoritam praktično je izveden korištenjem programskog okruženja

The generator group of voltage zone North also includes the Croatian part of NPP Krško, i.e., it is assumed that the Croatian TSO administers a half of the control range of that power plant and that, consequently, the power plant participates on equal basis in the submission of bids for the supply of reactive power within a limited range. From the available network reactive compensation devices installed within the Croatian EPS a 100 Mvar inductor has been modeled, installed in SS Ernestinovo, and a 3x16 Mvar capacitor bank, installed in SS Đakovo. Both devices are deployed within zone North. The costs of reactive power generation by the network reactive compensation devices are presumed fixed and worth 0,05 EUR/Mvar.

The proposed optimization algorithm has been practically derived by using the MATLAB software računalnog paketa MATLAB. U izradi koda optimizacijskog algoritma djelomično je korišten Matpower [18], računalni program otvorenog tipa, izrađen također u MATLAB okruženju. U prvom optimizacijskom koraku za rješavanje problema optimalnih tokova snaga korištena je primal-dual metoda unutarnje točke, temeljena na Mehrotrinom prediktor-korektor algoritmu [19] i [20] koja je sastavni dio MATLAB Optimization Toolbox paketa [21]. U pozadini leži računalni program Lipsol [22], koji je iskorišten u okviru MATLAB okruženja. Kvadratne krivulje troškova proizvodnje jalove snage sinkronih generatora linearizirane su putem dovoljnog broja točaka.

U naponskoj zoni Sjever prihvaćeno je, nakon provedenog prvog koraka optimizacije, osam ponuda od ukupno deset mogućih. Korištenjem dražbene metode određena je jedinstvena zonska cijena jalove energije, a svi su prihvaćeni ponuđači unutar naponske zone plaćeni za svoju uslugu prema zonskoj cijeni, tablica 3. Generator TE Sisak 220 kV imao je, temeljem angažmana određenog proračunom optimalnih tokova snaga, najvišu marginalnu cijenu u naponskoj zoni Sjever, u iznosu 0,21 EUR/Mvar. Za generatore PTE Osijek i TE Sisak 110 kV proračunati angažman daje zanemariv marginalan trošak proizvodnje jalove snage te ove dvije ponude nisu ušle u dražbeni postupak. Kondenzatorska baterija u TS Đakovo postavljena je u najviši mogući položaj (48 Mvar).

environment. Partially used in the creation of the optimization algorithm code was the Matpower open-type software package [18], also created in the MATLAB environment. In the first optimization step for solving the problem of optimal power flows the primal dual interior-point method was used, based on Mehrotra's predictor-corrector algorithm [19] and [20], which is a constituent part of the MATLAB Optimization Toolbox package [21]. In the background is the Lipsol package [22], used under MATLAB environment. The square cost curves of reactive power generation by the synchronous generators are linearized by a sufficient number of points.

In zone North, eight out of ten possible bids have been accepted upon completion of the first optimization step. By using the auction method, a uniform zonal price of reactive energy has been defined and all accepted bidders within the voltage zone have been paid for their service according to the zonal price, Table 3. The generator of TPP Sisak 220 kV, based on the calculation-defined engagement of optimal power flows, reached the highest marginal price in zone North, amounting 0,21 EUR/Mvar. For the generators of TPP Osijek and TPP Sisak 110 kV the calculated engagement gives a negligible marginal cost of reactive power generation, so these two bids did not qualify for the auction procedure. The capacitor bank at SS Đakovo is set in the highest possible position (48 Mvar).

Tablica 3 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Sjever
Table 3 – Results of the first optimization step and auction procedure in zone North

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
EL-TO / CHP EL-TO 110 kV	6,67	0,09	1,43
HE / HPP Čakovec 110 kV	7,22	0,11	1,55
HE / TPP Dubrava 110 kV	7,22	0,11	1,55
HE / TPP Varaždin 110 kV	11,44	0,12	2,46
NE / NPP Krško 400 kV	11,11	0,14	2,39
PTE / TPP Osijek 110 kV**	3,00	0,00	0,00
TE-TO / CHP 1 110 kV	7,22	0,08	1,55
TE-TO / CHP 2 110 kV	10,00	0,11	2,15
TE / TPP Sisak 220 kV	14,33	0,21*	3,08
TE / TPP Sisak 110 kV**	1,57	0,00	0,00

* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy
** Ponuda nije prihvaćena / Bid not accepted

Prvi korak optimizacije naponske zone Sjever proveden je za dva dodatna slučaja. U prvom slučaju uklonjena je kondenzatorska baterija u TS Đakovo kako bi se analizirao utjecaj nedostatka jalove snage na promjenu marginalne zonske cijene jalove snage. Nakon provedenog optimizacijskog

The first step in optimizing zone North has been taken in two additional cases. In one case the capacitor bank at SS Đakovo was removed to enable an analysis of the impact of the lack of reactive power on the change in the marginal zonal price of reactive power. Upon completed optimization proračuna i dražbenog postupka uočljivo je da je marginalna cijena proizvodnje jalove snage u zoni Sjever porasla, tablica 4, a ponuđač s najvišom marginalnom cijenom (engl. price-setter), nije više TE Sisak 220 kV, iako je i njegova marginalna cijena u odnosu na prethodni slučaj porasla, već je to u predmetnom slučaju EL-TO Zagreb. Ukupna proizvodnja jalove snage generatora se povećala, a time i ukupno plaćanje OPS-a za jalovu energiju, dok se pričuva jalove snage u generatorima smanjila. Uočljiv je stoga i ekonomski i tehnički, odnosno sigurnosni, utjecaj nedostatka mrežnih kompenzacijskih uređaja u dijelovima sustava deficitarnima proizvodnjom jalove snage.

Drugi obrađeni slučaj tiče se poštivanja trenutačno vrijedećih odredbi iz Mrežnih pravila elektroenergetskog sustava [23] gdje u točki 4.1.6 Usluge sustava, podtočka 4.1.6.5 Održavanje napona i kompenzacija jalove snage, stoji da elektrana ima pravo na naknadu troškova zbog povećanog gubitka djelatne snage samo u slučaju da prema zahtjevu OPS-a isporučuje u mrežu jalovu snagu izvan obveznog regulacijskog opsega kojeg moraju ispoštovati sve proizvodne jedinice priključene na prijenosnu mrežu, a koji iznosi između 0,95 induktivno i 0,95 kapacitivno. To u konkretnom slučaju znači da niti jedan ponuđač nije odabran nakon provedene dražbe budući da je optimizacijskim proračunom proizvodnja jalove snage svake uključene elektrane unutar obveznog regulacijskog opsega, tablica 5. Time bi se izbjeglo plaćanje OPS-a za jalovu energiju, dok bi se plaćanje za regulacijski opseg, odnosno raspoloživost i nadalje provodilo prema uvjetima iz godišnjeg natječaja. Opisani primjer odražava mogućnosti i posljedice praktične primjene predložene metodologije unutar hrvatskog EES-a.

and auction procedure it is obvious that marginal price of generated reactive power in zone North has gone up, Table 4, whereas the price setter is no longer the TPP Sisak 220 kV, although its marginal price has also gone up in relation to the previous case, the price setter in the subject case is now the CHP Zagreb. The total reactive power output of the generators has increased and so has the TSO's total payment for reactive energy as a result, whereas the reactive power reserve in the generators has decreased. Hence the noticeable economic as well as technical and security impact of the lack of network reactive compensation devices in the parts of the system short of reactive power generation.

The other analyzed case concerns the observance of the currently valid provisions of the EPS Network Rules [23], where in section 4.1.6 System Services, subsection 4.1.6.5 Voltage Maintenance and Reactive Power Compensation, it is stated that a power plant is entitled to cost compensation on account of an increased active power loss only if at the TSO's request the plant supplies the network with reactive power outside the mandatory control range that must be observed by all generation facilities connected to the transmission network, amounting between 0,95 inductively and 0,95 capacitively. What it means in the concrete case is that no bidder has been selected during the auction, because under the performed optimization the reactive power output of each switched-on power plant is within the mandatory control range, Table 5. The TSO's payment for reactive energy would thus be avoided, whereas the payment for the control range, or availability, would be continued under the terms and conditions of the annual tender. The described example illustrates the potentials and effects of the practical application of the proposed methodology within the Croatian EPS.

Tablica 4 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Sjever za slučaj bez kondenzatorske baterije u TS Đakovo
Table 4 – Results of the first optimization step and auction procedure in zone North for a case without the capacitor bank at SS Đakovo

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
EL-TO / CHP EL-TO 110 kV	13,33	0,26*	3,49
HE / HPP Čakovec 110 kV	11,67	0,19	3,05
HE / HPP Dubrava 110 kV	11,67	0,19	3,05
HE / HPP Varaždin 110 kV	19,54	0,25	5,11
NE / NPP Krško 400 kV	11,11	0,14	2,91
PTE / TPP Osijek 110 kV	10,00	0,18	2,62
TE-TO / CHP 1 110 kV	7,22	0,09	1,89
TE-TO / CHP 2 110 kV	10,00	0,11	2,62
TE / TPP Sisak 220 kV	14,33	0,22	3,75
TE / TPP Sisak 110 kV	14,00	0,25	3,66

* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy

Tablica 5 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Sjever u slučaju uvažavanja odredbi Mrežnih pravila

Table 5 – Results of the first optimization step and auction procedure in zone North for a case where the provisions of the Network Rules are observed

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
EL-TO / CHP EL-TO 110 kV**	6,67	0,00	0,00
HE / HPP Čakovec 110 kV**	7,22	0,00	0,00
HE / TPP Dubrava 110 kV**	7,22	0,00	0,00
HE / TPP Varaždin 110 kV**	11,44	0,00	0,00
NE / NPP Krško 400 kV**	11,11	0,00	0,00
PTE / TPP Osijek 110 kV**	3,00	0,00	0,00
TE-TO / CHP 1 110 kV	7,22	0,00	0,00
TE-TO / CHP 2 110 kV	10,00	0,00	0,00
TE / TPP Sisak 220 kV**	14,33	0,00	0,00
TE / TPP Sisak 110 kV**	1,57	0,00	0,00

** Ponuda nije prihvaćena / Bid not accepted

U naponskoj zoni Zapad prihvaćene su, nakon provedenog prvog koraka optimizacije, sve raspoložive ponude. Korištenjem dražbene metode određena je jedinstvena zonska cijena jalove energije, a svi su prihvaćeni ponuđači unutar naponske zone plaćeni za svoju uslugu prema zonskoj cijeni, tablica 6. Generator TE Plomin 220 kV imao je, temeljem angažmana određenog proračunom optimalnih tokova snaga, najvišu marginalnu cijenu u naponskoj zoni Zapad, u iznosu 1,25 EUR/Mvar.

Prvi korak optimizacije naponske zone Zapad proveden je i za slučaj poštivanja trenutačno vrijedećih odredbi iz Mrežnih pravila elektroenergetskog sustava. Samo su dvije ponude, od raspoloživih sedam, prihvaćene, tablica 7. Generator HE Vinodol imao je u ovom slučaju najvišu marginalnu cijenu, u iznosu 0,79 EUR/Mvar.

U naponskoj zoni Jug prihvaćene su, nakon provedenog prvog koraka optimizacije, sve raspoložive ponude. Korištenjem dražbene metode određena je jedinstvena zonska cijena jalove energije, a svi su prihvaćeni ponuđači unutar naponske zone plaćeni za svoju uslugu prema zonskoj cijeni, tablica 8. Generator HE Dubrovnik imao je, temeljem angažmana određenog proračunom optimalnih tokova snaga, najvišu marginalnu cijenu u naponskoj zoni Jug, u iznosu 0,42 EUR/Mvar.

In zone West all the available bids have been accepted after completion of the first optimization step. The uniform zonal price of reactive energy has been defined by using the auction method, and all the accepted bidders within the voltage zone have been paid for their service according to the zonal price, Table 6. The generator of TPP Plomin 220 kV, based on the calculation-defined engagement of optimal power flows, reached the highest marginal price in zone West, amounting 1,25 EUR/Mvar.

The first step in optimizing zone West has also been taken for the case of observance of the currently valid provisions contained in the EPS Network Rules. Only two out of available seven bids have been accepted, Table 7. The generator of HPP Vinodol had in this case the highest marginal price amounting 0,79 EUR/Mvar.

In zone South all available bids have been accepted after completion of first optimization step. The uniform zonal price of reactive energy has been defined by using the auction method, and all the accepted bidders within the voltage zone have been paid for their service according to the zonal price, Table 8. The generator of HPP Dubrovnik based on the calculation-defined engagement of optimal power flows, reached the highest marginal price in zone South, amounting 0,42 EUR/Mvar.

Tablica 6 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Zapad
Table 6 – Results of the first optimization step and auction procedure in zone West

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
HE / HPP Senj 220 kV	–1,57	0,05	1,96
HE / HPP Senj 110 kV	–8,91	0,12	11,10
HE / HPP Vinodol 110 kV	54,27	0,79	67,59
HE / HPP Sklope 110 kV	10,40	0,20	12,95
TE / TPP Plomin 220 kV	61,06	1,25*	76,05
TE / TPP Plomin 110 kV	32,00	1,03	39,86
TE / TPP Rijeka 220 kV	48,00	0,90	59,78

* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy

Tablica 7 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Zapad u slučaju uvažavanja odredbi Mrežnih pravila
Table 7 – Results of the first optimization step and auction procedure in zone West in the case of observance of the provisions of the Network Rules

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
HE / HPP Senj 220 kV**	–1,57	0,00	0,00
HE / HPP Senj 110 kV**	–8,91	0,00	0,00
HE / HPP Vinodol 110 kV	54,27	0,79*	42,82
HE / HPP Sklope 110 kV	10,40	0,20	8,21
TE / HPP Plomin 220 kV**	61,06	0,00	0,00
TE / HPP Plomin 110 kV**	32,00	0,00	0,00
TE / HPP Rijeka 220 kV**	48,00	0,00	0,00

* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy
** Ponuda nije prihvaćena / Bid not accepted

Tablica 8 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Jug
Table 8 – Results of the first optimization step and auction procedure in zone South

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
HE / HPP Dubrovnik 110 kV	20,79	0,42*	6,09
HE / HPP Orlovac 220 kV	16,78	0,24	4,91
HE / HPP Peruća 110 kV	13,07	0,17	3,83
HE / HPP Zakučac 220 kV	12,78	0,21	3,74
HE / HPP Zakučac 110 kV	17,00	0,29	4,98
HE / HPP Đale 110 kV	13,00	0,23	3,81
RHE / PSHPP Velebit 400 kV	11,00	0,16	3,22

* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy

Prvi korak optimizacije naponske zone Jug proveden je, kao i u slučaju zona Sjever i Zapad, i za slučaj poštivanja trenutačno vrijedećih odredbi iz Mrežnih pravila elektroenergetskog sustava. Samo je jedna ponuda, od raspoloživih sedam, prihvaćena, tablica 9. Generator HE Đale imao je u

The first step of optimizing zone South has also been taken, as in the cases of zones North and West, for the case of observance of the currently valid provisions of the EPS Network Rules. Only one out of available seven bids has been accepted, Table 9. The generator of HPP Đale had in this ovom slučaju najvišu marginalnu cijenu, u iznosu 0,23 EUR/Mvar.

case the highest marginal price amounting 0,23 EUR/Mvar.

Tablica 9 – Rezultati prvog koraka optimizacije i dražbenog postupka u naponskoj zoni Jug u slučaju uvažavanja odredbi Mrežnih pravila
Table 9 – Results of the first optimization step and auction procedure in zone South in the case of observance of the provisions of the Network Rules

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
HE / HPP Dubrovnik 110 kV**	20,79	0,00	0,00
HE / HPP Orlovac 220 kV**	16,78	0,00	0,00
HE / HPP Peruća 110 kV**	13,07	0,00	0,00
HE / HPP Zakučac 220 kV**	12,78	0,00	0,00
HE / HPP Zakučac 110 kV**	17,00	0,00	0,00
HE / HPP Đale 110 kV**	13,00	0,23*	2,97
RHE / PSHPP Velebit 400 kV**	11,00	0,00	0,00

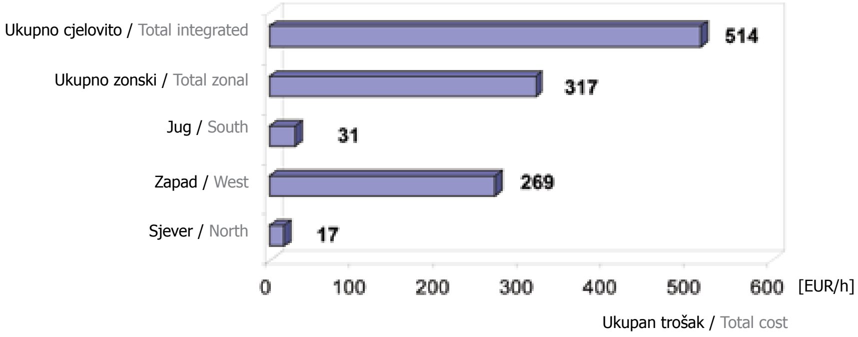
* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy
** Ponuda nije prihvaćena / Bid not accepted

Nakon provedenog dražbenog postupka u sve tri naponske zone, primjetne su značajne razlike u postignutim jedinstvenim zonskim cijenama iako su krivulje troškova slične za sve raspoložive elektrane, uz određene razlike u troškovima proizvodnje jalove snage između hidro i turbo agregata. Najniža je cijena postignuta u naponskoj zoni Sjever (0,21 EUR/Mvar) što je i očekivano s obzirom na najveći broj raspoloživih agregata te postojanje kondenzatorske baterije. U naponskoj zoni Jug postignuta je dvostruko veća cijena (0,42 EUR/Mvar) u odnosu na zonu Sjever, dok je u zoni Zapad jedinstvena cijena jalove snage čak šest puta veća u odnosu na zonu Sjever (1,25 EUR/Mvar). Pri ovako izrazitim razlikama u značajkama svake pojedine naponske zone u smislu potreba za jalovom snagom i raspoloživosti izvora jalove snage te njihovih troškova, posebno dolazi do izražaja prednost podjele EES-a u lokalna tržišta jalovom snagom kako je to predloženo u predmetnom istraživanju.

Stoga je prvi korak optimizacije proveden i za primjer cijelog hrvatskog EES-a kao jedne naponske zone, kako bi se na taj način dobila usporedba zonskog i cjelovitog pristupa, tablica 10. Generator TE Plomin 220 kV imao je, temeljem angažmana određenog proračunom optimalnih tokova snaga, najvišu marginalnu cijenu, u iznosu 1,22 EUR/Mvar. Kao što je i pretpostavljeno, minimiziranje troškova proizvodnje jalove snage odvojeno po zonama daje niže ukupne troškove nego minimiziranje cijele mreže kao jedne naponske zone. Slika 7 daje usporedbu ukupnih OPS-ovih troškova plaćanja za jalovu energiju zonskog u odnosu na cjeloviti pristup.

After the conducted auction procedure in all the three voltage zones, significant differences in the achieved uniform zonal prices become noticeable, although the cost curves are similar for all the available power plants, with certain variations in reactive power generation costs between hydro and turbo sets. The lowest price was achieved in zone North (0,21 EUR/Mvar), which was expected in view of the greatest number of available generating sets and the existence of the capacitor bank. In zone South a price twice as high was achieved (0,42 EUR/Mvar) in relation to zone North, whereas in zone West the uniform price of reactive power is as much as six times higher in relation to zone North (1,25 EUR/Mvar). Given such marked differences in the characteristics of each individual voltage zone in terms of reactive power requirements and availability of reactive power sources, and their costs, the advantages of the division of the EPS into local reactive power markets, as propose in subject research, is particularly expressed.

That is why the first optimization step has also been carried out for the whole Croatian EPS as a single voltage zone, so as to get a comparison between the zonal and the integral approach, Table 10. The generator of TPP Plomin 220 kV, based on the calculation-defined engagement of optimal power flows, had the highest marginal price amounting 1,22 EUR/Mvar. As presumed, the minimization of reactive power generation costs carried out separately by zones yields lower total costs than the minimization of the whole network as a single voltage zone. Figure 7 gives a comparison of total TSO's payment costs for the reactive energy between the zonal and the integral approach.



Slika 7 — Usporedba OPS-ovih troškova plaćanja za jalovu energiju zonskog u odnosu na cjeloviti pristup
Figure 7 — Comparison of the TSO's payment costs for the reactive energy between the zonal and the integral approach

Tablica 10 – Rezultati prvog koraka optimizacije te dražbenog postupka za određivanje jedinstvene cijene jalove energije za hrvatski EES u cjelini
Table 10 – Results of the first optimization step and auction procedure aimed to define a uniform price of reactive energy for the Croatian EPS as a whole

Generator / Generator	Q_g [Mvar]	Marginalni trošak / Marginal cost [EUR/Mvar]	Plaćanje / Payment [EUR]
EL-TO / CHP EL-TO 110 kV	13,33	0,26	16,28
HE / HPP Čakovec 110 kV	11,00	0,18	13,43
HE / HPP Dubrava 110 kV	11,00	0,18	13,43
HE / HPP Dubrovnik 110 kV	19,12	0,39	23,34
HE / HPP Orlovac 220 kV	16,78	0,24	20,49
HE / HPP Peruća 110 kV	14,21	0,19	17,35
HE / HPP Senj 220 kV	5,00	0,06	6,11
HE / HPP Senj 110 kV	–3,00	0,03	3,66
HE / HPP Varaždin 110 kV	15,00	0,17	18,32
HE / HPP Vinodol 110 kV	50,00	0,73	61,05
HE / HPP Zakučac 220 kV	12,78	0,21	15,60
HE / HPP Zakučac 110 kV	17,00	0,29	20,76
HE / HPP Đale 110 kV	13,00	0,23	15,87
HE / HPP Sklope 110 kV	10,40	0,20	12,70
NE / NPP Krško 400 kV	13,00	0,16	15,87
PTE / TPP Osijek 110 kV	10,00	0,18	12,21
RHE / PSHPP Velebit 400 kV	11,00	0,16	13,43
TE-TO / CHP 1 110 kV	13,00	0,22	15,87
TE-TO / CHP 2 110 kV	10,00	0,11	12,21
TE / TPP Plomin 220 kV	60,00	1,22*	73,26
TE / TPP Plomin 110 kV	31,00	0,99	37,85
TE / TPP Rijeka 220 kV	46,00	0,86	56,17
TE / TPP Sisak 220 kV	8,00	0,09	9,77
TE / TPP Sisak 110 kV	7,00	0,10	8,55

* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy

Nakon što je proveden prvi korak optimizacijskog proračuna te dražbenim postupkom određene jedinstvene zonske cijene jalove energije, pristupilo se minimiziranju ukupnih troškova OPS-a te time i određivanju optimalnog naponskog plana hrvatskog EES-a za scenarij maksimalnog opterećenja.

Once the first optimization step was made and the uniform zonal prices of reactive energy defined through auction, the minimization of the TSO's total costs followed next and thereby the definition of the optimal voltage plan of the Croatian EPS for a maximum load scenario. Calculations were

Proračuni su provedeni za nekoliko pretpostavljenih cijena djelatne energije za pokriće gubitaka u mreži, tablica 11, gdje je C_{GUB} cijena djelatne energije za pokriće gubitaka u mreži, P_{GUB} je vrijednost gubitaka djelatne snage u mreži, T_{GUB} su troškovi nabave djelatne energije za pokriće gubitaka u mreži, T_{Q} troškovi nabave jalove energije, a T_{UK} ukupni troškovi OPS-a po satu. Zonske cijene jalove energije za prikazani slučaj iznosile su 0,21 EUR/Mvarh (Sjever), 1,25 EUR/Mvarh (Zapad) i 0,42 EUR/Mvarh (Jug), prema rezultatima prvog optimizacijskog koraka (tablice 3, 6 i 8). Tablica 12 daje usporedbu vrijednosti proizvodnje jalove snage generatorskih čvorišta i naknade svakom generatoru za proizvedenu jalovu energiju, s obzirom na zonske cijene jalove energije, za tri pretpostavljene cijene djelatne energije za pokriće gubitaka u mreži.

Prijenosni omjeri transformatora s mogućnošću promjene prijenosnog omjera pod opterećenjem također su bili dio skupa upravljačkih varijabli proračuna optimalnih tokova snaga. U proračun su bili uključeni svi raspoloživi mrežni transformatori u hrvatskom EES-u koji u naravi imaju mogućnost promjene prijenosnog omjera pod opterećenjem. Tablica 13 daje usporedbu vrijednosti prijenosnih omjera tranformatora u početnom stanju i za tri pretpostavljene cijene djelatne energije za pokriće gubitaka u mreži.

Korištena je metoda sekvencijalnog kvadratnog programiranja [23], koja je postavljeni višekriterijski optimizacijski problem uspješno riješila. Ime korištene funkcije je Fmincon i sastavni je dio MATLAB Optimization Toolbox paketa. Rezultati drugog optimizacijskog koraka su u granicama očekivanih. Viša cijena djelatne energije za pokriće gubitaka u mreži, C_{GUB}, rezultira povećavanjem vrijednosti težinskog faktora prvog izraza u višekriterijskoj funkciji cilja, izraz (14), odnosno većim troškovima nabave djelatne energije, T_{GUB}.

made for several assumed prices of active power for the coverage of network losses, Table 11, where C_{GUB} is the price of active energy for the coverage of network losses, P_{GUB} is the value of active power losses in the network, T_{GUB} are active energy procurement costs for the coverage of network losses, T_{Q} are reactive power procurement costs, and T_{UK} are the TSO's total hourly costs. The zonal prices of reactive energy for the demonstrated case amounted to 0,21 EUR/Mvarh (North), 1,25 EUR/Mvarh (West) and 0,42 EUR/Mvarh (South), according to the results of the first optimization step (Tables 3, 6 and 8). Table 12 gives a comparison of reactive power generation values of generator nodes and compensation to each generator for generated reactive energy, relative to zonal prices of reactive energy, for three assumed active energy prices for the coverage of network losses.

The transmission ratios of ULTC transformers were also a part of the set of control variables of the optimal power flow. The calculation comprised all available network transformers in the Croatian EPS which in practice are capable of changing the transmission ratio under load. Table 13 gives a comparison of the ratio values of transformers in the initial state and for three assumed active energy prices for the coverage of network losses.

The sequential square programming method was used [23], the one which successfully solved the multi-criterion optimization problem. The used function is named Fmincon and is a constituent part of the MATLAB Optimization Toolbox package. The results of the second optimization step are within the expected margins. The higher price of active energy for the coverage of network losses, C_{GUB}, results in the increasing value of the weight factor of the first expression in the multi-criterion goal function, expression (14), or higher active energy procurement costs, T_{GUB}.

Tablica 11 – Rezultati drugog koraka optimizacije obzirom na različite cijene djelatne energije za pokriće gubitaka u mreži

Table 11 – Results of the second optimization step relative to different active energy prices for the coverage of network losses

C_{GUB} [EUR/MWh]	P_{GUB} [MW]	T_{GUB} [EUR]	T_{Q} [EUR]	T_{UK} [EUR]
10	96,5	964,6	551,0	1637,6
30	94,0	2820,9	560,5	3381,4
50	92,5	4625,0	610,0	5242,0
70	87,7	6135,8	639,0	6774,8
90	85,0	7646,4	334,0	8003,4

Tablica 12 – Usporedba vrijednosti proizvodnje jalove snage generatorskih čvorišta i naknade svakom generatoru za proizvedenu jalovu energiju
Table 12 – Comparison of reactive power generation values of generator nodes and compensation to each generator for generated reactive energy

Generator / Generator	C_{GUB} [EUR/MWh]					
	10		50		90	
	Q_g [Mvar]	T_Q [EUR]	Q_g [Mvar]	T_Q [EUR]	Q_g [Mvar]	T_Q [EUR]
EL-TO / CHP EL-TO 110 kV	61	13	35	7	25	5
HE / HPP Čakovec 110 kV	26	5	–15	3	–13	3
HE / HPP Dubrava 110 kV	26	5	–15	3	10	2
HE / HPP Dubrovnik 110 kV	5	2	0	0	33	14
HE / HPP Orlovac 220 kV	93	39	56	23	31	13
HE / HPP Peruća 110 kV	–20	8	–22	9	–9	4
HE / HPP Senj 220 kV	5	6	13	16	–8	10
HE / HPP Senj 110 kV	–73	92	–70	87	–61	76
HE / HPP Varaždin 110 kV	58	12	–21	4	2	0
HE / HPP Vinodol 110 kV	–4	5	–11	14	22	27
HE / HPP Zakučac 220 kV	160	67	104	44	43	18
HE / HPP Zakučac 110 kV	–58	24	–68	29	–60	25
HE / HPP Đale 110 kV	–6	2	–14	6	3	1
HE / HPP Sklope 110 kV	–4	6	–13	16	1	1
NE / NPP Krško 400 kV	283	59	172	36	138	29
PTE / TPP Osijek 110 kV	7	1	17	4	–33	7
RHE / PSHPP Velebit 400 kV	–17	7	69	29	30	13
TE-TO / CHP 1 110 kV	59	12	15	3	24	5
TE-TO / CHP 2 110 kV	–29	6	–40	8	119	25
TE / TPP Plomin 220 kV	–14	17	–41	51	15	18
TE / TPP Plomin 110 kV	1	1	11	13	23	29
TE / TPP Rijeka 220 kV	91	113	159	199	3	4
TE / TPP Sisak 220 kV	216	45	–15	3	22	5
TE / TPP Sisak 110 kV	–47	10	–33	7	110	23
Ukupno / Total	866	551	306	610	359	334

Značajke naponskog profila u mreži s obzirom na rezultate proračuna optimalnih tokova snaga u prvom i drugom optimizacijskom koraku mijenjaju se s obzirom na promatrane naponske zone. Dok je u zoni Sjever naponski profil nakon prvog optimizacijskog koraka sličan rezultatima tokova snaga, u drugom optimizacijskom koraku srednja vrijednost napona u zoni je povišena, ali je uravnoteženost naponskog profila narušena. U zoni Zapad rezultati prvog optimizacijskog koraka daju višu srednju vrijednost napona s obzirom na proračun tokova snaga, dok je u drugom optimizacijskom koraku srednja vrijednost napona u zoni neznatno snižena, a uravnoteženost naponskog profila je narušena. U zoni Jug srednja vrijednost napona je snižena nakon provedenog prvog optimizacijskog koraka u odnosu na rezultate proračuna tokova snaga, dok drugi korak optimizacije

The voltage profile characteristics in the network in respect of the results of the optimal power flow in the first and second optimization steps are changing relative to the observed voltage zones. While in zone North the voltage profile after the first optimization step is similar to the power flow results, in the second optimization step the mean voltage value in the zone is heightened, but the voltage profile balance is disrupted. In zone West the results of the first optimization step give a higher mean voltage value relative to the power flow calculation, whereas in the second optimization step the mean voltage value in the zone is slightly lower and the voltage profile balance is disrupted. In zone South the mean voltage value is lower after the first optimization step relative to the power flow calculation results, whereas the second optimization step yields a higher mean voltage value daje višu srednju vrijednost napona u odnosu na rezultate proračuna tokova snaga, no uravnoteženost naponskog profila je narušena.

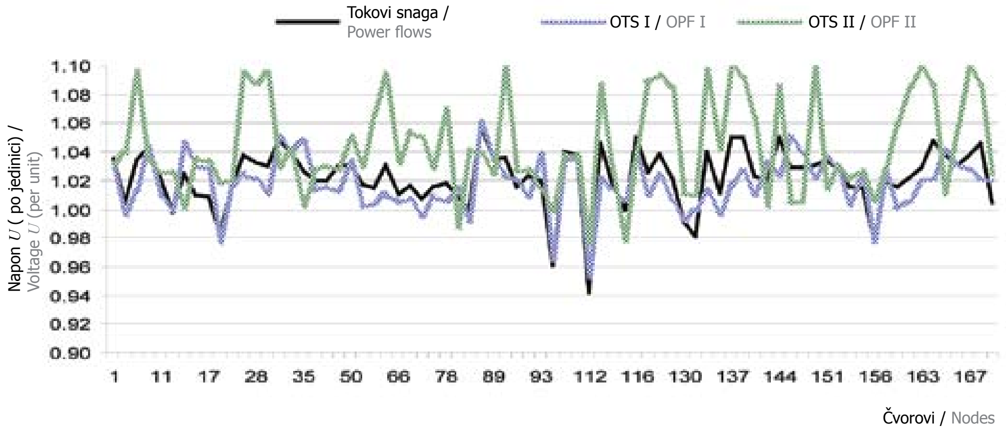
Slike 8, 9 i 10 prikazuju usporedbu naponskog profila za različite faze proračuna, za tri naponske zone. Slike 11, 12 i 13 prikazuju usporedbu proizvodnje jalove snage angažiranih izvora za različite faze proračuna, za tri naponske zone. Početno stanje predstavlja rezultate tokova snaga, OTS I odnosi se na prvi, a OTS II na drugi korak optimizacijskog proračuna uz cijenu djelatne energije za pokriće gubitaka u mreži C_{GUB} = 50 EUR/MWh. Na slici 14 dana je usporedba srednjih vrijednosti iznosa napona svih čvorišta mreže za različite faze proračuna, za tri naponske zone.

relative to the power flow calculation results, but the voltage profile balance is disrupted.

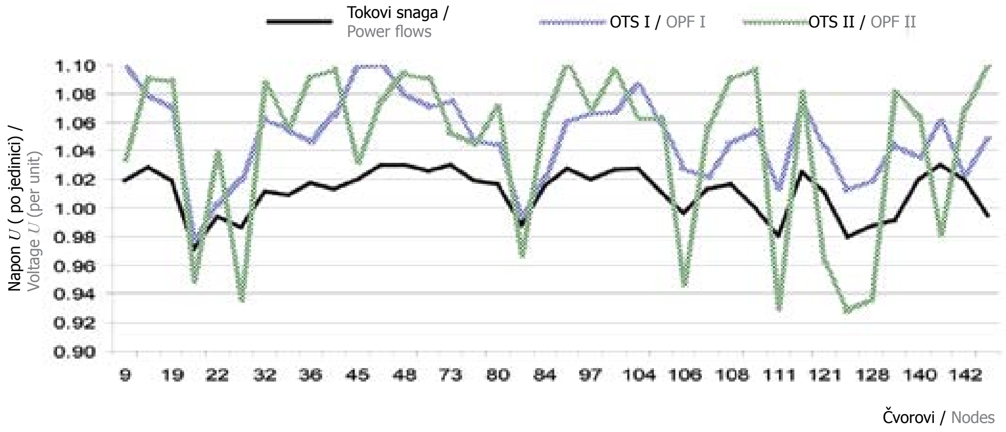
Figures 8, 9 and 10 give a comparison of the voltage profile for different calculation stages, for three voltage zones. Figures 11, 12 and 13 give a comparison of reactive power generation by engaged sources for different calculation stages, for three voltage zones. The initial state represents the power flow results, OPF I relates to the first, OPF II to the second calculation optimization step with the price of active energy for the coverage of network losses C_{GUB} = 50 EUR/MWh. Figure 14 gives a comparison of mean voltage values of all network nodes for different calculation stages, for three voltage zones.

Tablica 13 – Usporedba vrijednosti prijenosnih omjera tranformatora u početnom stanju i za tri pretpostavljene cijene djelatne energije za pokriće gubitaka u mreži
Table 13 – Comparison of the values of transformer transmission ratios in the initial state and for three presumed prices of active energy for the coverage of network losses

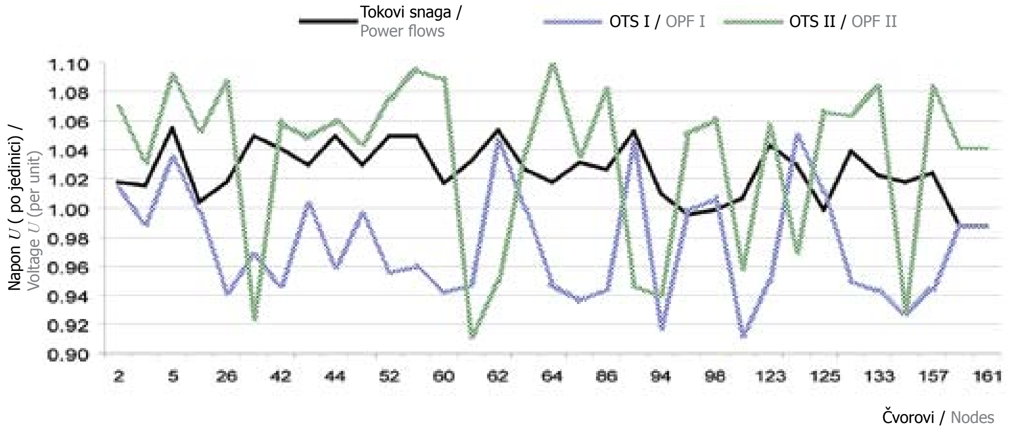
ULTC Transformator / ULTC Transformer	U_{n1} / U_{n2} (p.u.)			
	Početno stanje / Initial state	C_{GUB} [EUR/MWh]		
		10	50	90
Bilice 220/110 kV	1,00	1,00	0,91	0,90
Bilice 220/110 kV	1,00	1,00	0,95	0,97
Đakovo 220/110 kV	1,00	0,90	0,95	0,90
Ernestinovo 400/110 kV	1,00	1,02	0,99	1,03
Ernestinovo 400/110 kV	1,00	1,03	0,99	1,04
HE / HPP Senj 220/110 kV	1,00	1,03	0,93	0,95
HE / HPP Zakučac 220/110 kV	1,00	0,93	0,90	0,99
Konjsko 220/110 kV	1,00	0,90	0,90	0,90
Konjsko 220/110 kV	1,00	0,90	0,90	0,90
Međurić 220/110 kV	1,00	0,90	0,93	1,00
Melina 220/110 kV	1,00	0,97	0,92	0,99
Mraclin 220/110 kV	1,00	0,90	0,90	0,92
Mraclin 220/110 kV	1,00	0,90	0,90	0,90
Pehlin 220/110 kV	1,00	0,90	0,91	0,90
TE / TPP Plomin 220/110 kV	1,00	1,10	1,10	1,02
TE / TPP Plomin 220/110 kV	1,00	1,10	1,10	0,99
TE / TPP Sisak 220/110 kV	1,00	0,99	0,90	1,02
Žerjavinec 400/220 kV	1,00	0,96	0,90	0,95
Žerjavinec 400/110 kV	1,00	1,01	0,90	1,00
Žerjavinec 400/110 kV	1,00	1,01	0,90	1,02



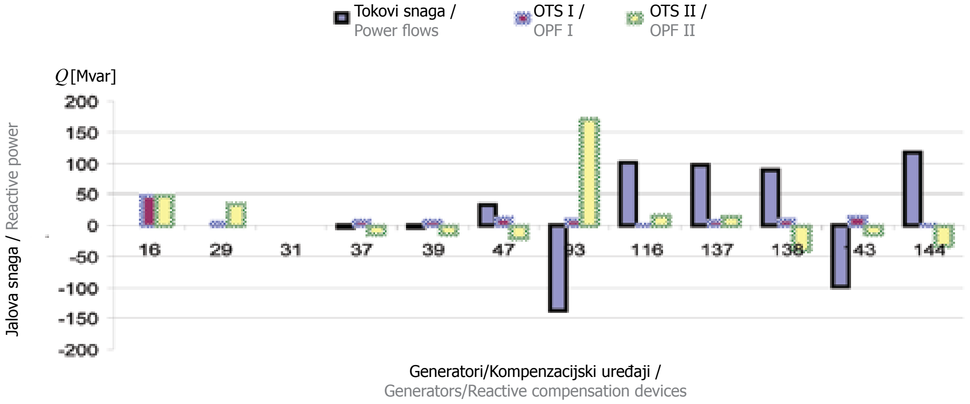
Slika 8 — Usporedba naponskog profila u zoni Sjever za različite faze proračuna
Figure 8 — Voltage profile comparison in zone North for different calculation stages



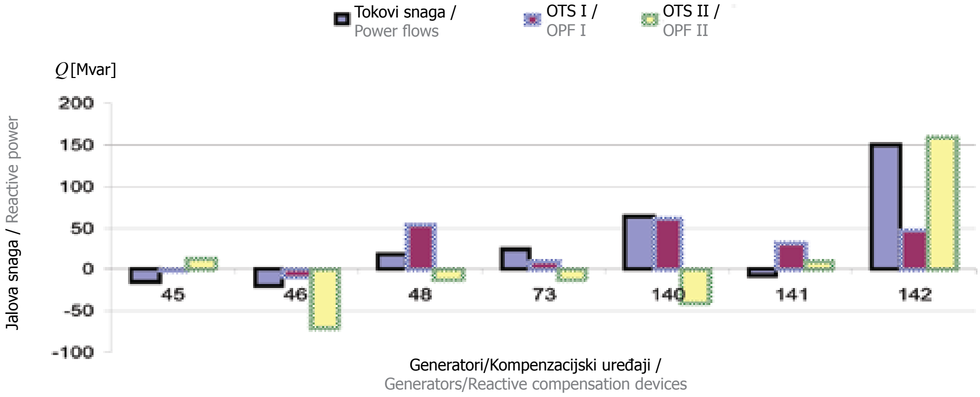
Slika 9 — Usporedba naponskog profila u zoni Zapad za različite faze proračuna
Figure 9 — Voltage profile comparison in zone West for different calculation stages



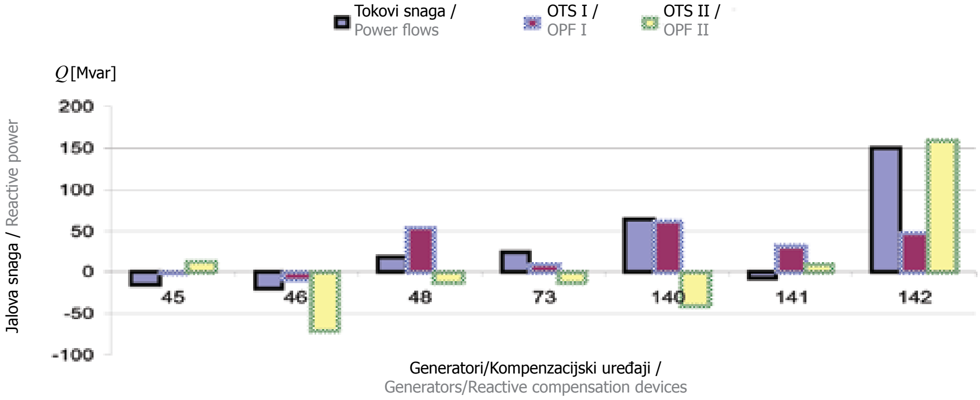
Slika 10 — Usporedba naponskog profila u zoni Jug za različite faze proračuna
Figure 10 — Voltage profile comparison in zone South for different calculation stages



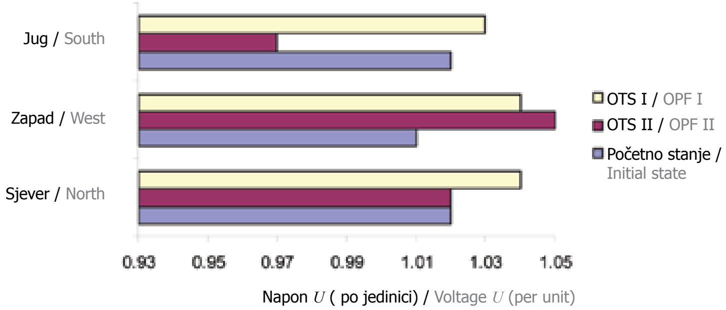
Slika 11 — Usporedba proizvodnje jalove snage angažiranih izvora u zoni Sjever za različite faze proračuna
Figure 11 — Comparison of reactive power generation by engaged sources in zone North for different calculation stages



Slika 12 — Usporedba proizvodnje jalove snage angažiranih izvora u zoni Zapad za različite faze proračuna
Figure 12 — Comparison of reactive power generation by engaged sources in zone West for different calculation stages



Slika 13 — Usporedba proizvodnje jalove snage angažiranih izvora u zoni Jug za različite faze proračuna
Figure 13 — Comparison of reactive power generation by engaged sources in zone South for different calculation stages



Slika 14 — Usporedba srednjih vrijednosti iznosa napona čvorova naponskih zona za različite faze proračuna
Figure 14 — Comparison of mean voltage values of voltage zone nodes for different calculation stages

5 ZAKLJUČAK

Razvijena metodologija vrednovanja jalove snage rješava problem osiguranja pomoćne usluge $U-Q$ regulacije tržišnim pristupom. Podjelom EES-a u naponske zone uspostavljaju se zasebna tržišta jalovom snagom, čime se minimiziraju troškovi osiguranja pomoćne usluge $U-Q$ regulacije. Primijenjen je pristup jedinstvene cijene jalove snage unutar jedne naponske zone. Zonska cijena proizvodnje jalove snage oslikava prilike u naponskoj zoni u smislu dostatnosti izvora jalove snage. Metodologija u konačnici osigurava isporučiteljima pomoćne usluge $U-Q$ regulacije financijsku nadoknadu za raspoloživost, odnosno regulacijski opseg, te za stvarno proizvedenu jalovu energiju, pokrivajući time i fiksni i varijabilni dio troškova. Oba optimizacijska koraka, osim zadovoljenja postavljenih ekonomskih kriterija, imaju sljedeće pozitivne učinke na sigurnost pogona EES-a: naponski profil u mreži poboljšan je u odnosu na početno stanje te se maksimizira dinamička pričuva jalove snage u generatorima/elektranama.

Deficit jalove snage u određenoj zoni utječe na porast zonske cijene proizvodnje jalove snage, no ne utječe na zonske cijene ostalih naponskih zona što, u konačnici, ima za posljedicu smanjenje ukupnog troška OPS-a za osiguranje pomoćne usluge $U-Q$ regulacije u odnosu na cjeloviti pristup (cijela mreža kao jedna naponska zona). Uklopno stanje mreže ne utječe značajno na promjene granica naponskih zona određenih metodom električnih udaljenosti, dok utjecaj na promjenu pripadnost određene elektrane nekoj zoni nije uočen za razmatranu mrežu.

Korištenje složene funkcije cilja u drugom optimizacijskom koraku predložene metodologije, s dva kriterija vrednovana odgovarajućim cijenama kao težinskim faktorima, zahitjeva primjenu složenih nelinearnih optimizacijskih metoda. Pri tome, veličina problema i početni uvjeti znatno utječu na

5 CONCLUSION

A developed reactive power evaluation methodology solves the problem of providing the voltage control ancillary services on the principles of market economy. Through the division of the EPS into voltage zones separate reactive power markets are established, whereby the costs of voltage control ancillary service are minimized. The approach of a uniform price of reactive power within a voltage zone has been adopted. The zonal price of reactive power generation reflects the circumstances prevailing in a voltage zone in terms of sufficient reactive power sources. Ultimately, the methodology ensures for the providers of the voltage control ancillary service financial compensation for the availability, i.e., control range, and for the actually generated reactive energy, thereby covering both fixed and variable costs. Either optimization step, apart from meeting the set economic criteria, has the following positive effects on the ESP's operation security: voltage profile in the network is improved in comparison with the initial state and the dynamic reactive power reserve in the generators/power plants is maximized.

The deficit of reactive power in a zone influences the rise in the zonal prices of reactive power generation, but does not affect the zonal prices in other voltage zones, which in the end results in the reduction of the TSO's total cost of the provision of the voltage control ancillary service relative to the integral approach (the whole network being a single voltage zone). The network's on-state does not significantly influence changes in the voltage zone boundaries defined by the electrical distance method, whereas no influence on the changed classification of a power plant under a zone has been noticed for the analyzed network.

The use of the complex goal function in the second optimization step of the proposed methodology, involving two criteria evaluated by corresponding konvergenciju proračuna optimalnih tokova snaga, a konačno rješenje je u pravilu lokalni optimum.

Krivulje troškova proizvodnje jalove snage predstavljaju moguću prepreku u praktičnoj primjeni predložene metodologije. Određivanje krivulje troškova proizvodnje jalove snage generatora najprikladnije je izvesti mjerenjima u pogonu. Prema trenutačnim saznanjima, mjerenja takve vrste nisu se do sada provodila za generatore u hrvatskom EES-u, što znači da bi bilo potrebno prvo odrediti metodologiju mjerenja i određivanja krivulje na temelju rezultata mjerenja, zatim provesti spomenuta mjerenja za sve agregate u pogonu.

prices as weight factors, requires the application of complex nonlinear optimization methods. In this regard the magnitude of the problem and the starting conditions greatly influence the convergence of the optimal power flows and the final solution is, as a rule, the local optimum.

The cost curves of reactive power generation present a possible obstacle to the practical application of the proposed methodology. The cost curves of reactive power generation by the generators are best defined by measurement during operation. As far as known at present, measurements of that type have never been performed so far for the generators in the Croatian EPS, which means that the methodology of measurement and curve plotting based on measurement results should be defined first, followed by the said measurement for all the generating units in operation.

LITERATURA / REFERENCES

[1] HAO S., PAPALEXOPOULOS A., Reactive Power Pricing and Management, IEEE Transactions on Power Systems, Vol. 12, No. 1, 1997
[2] SAUER P., OVERBYE T., GROSS G., ALVARADO F., OREN S., MOMOH J., Reactive Power Support Services in Electricity Markets, PSERC Report, 2001
[3] PLAVŠIĆ T., KUZLE I., Regulacija napona i jalove snage kao pomoćna usluga sustava, Energija, god. 54(2005), No. 5.
[4] FERC, Reactive Power Supply and Consumption, Staff Report, 2005
[5] ZHONG J., BHATTACHARYA K., Reactive Power as an Ancillary Service, IEEE Transactions on Power Systems, Vol. 16, No. 2, 2001
[6] GIL J.B., ROMAN G.S., RIOS J.J.A., MARTIN P.S., Reactive Power Pricing: A Conceptual Framework for Remuneration and Charging Procedures, IEEE Transactions on Power Systems, Vol. 15, No. 2, 2000
[7] EL-SAMAHY I., BHATTAACHARYA K., CANIZARES C., A Unified Framework for Reactive Power Management in Deregulated Electricity Market, Proceedings of IEEE/PES, Atlanta, 2006
[8] ZHONG J., NOBILE E., BOSE A., BHATTACHARYA K., Localized Reactive Power Markets Using the Concept of Voltage Control Areas, IEEE Transactions on Power Systems, Vol. 19, No. 3, 2004
[9] NOBILE E., BOSE A., A New Scheme for Voltage Control in a Competitive Ancillary Service Market, Proceedings of 14th Power Systems Computation Conf., Sevilla, Spain, 2002
[10] PLAVŠIĆ T., KUZLE I., Zonal Reactive Power Market Model Based On Optimal Voltage Scheduling, IEEE Africon 2007 Conference, Windhoek, Namibia, 2007
[11] LAGONOTTE P., SABONNADIERE J.C., PAUL J.P., LEOST J.Y., Structural Analysis of the Electrical System: Application to Secondary Voltage Control in France, IEEE Transactions on Power Systems, Vol. 4, No. 2, 1989
[12] LAGONOTTE P., The Different Electrical Distances, 10th PSCC, Graz, Austria, 1990
[13] GRAINGER J.J., STEVENSON W.D., Power System Analysis, McGraw-Hill, New York, 1994
[14] MOMOH J.A., Electric Power System Applications of Optimization, Marcel Dekker Inc., 2001
[15] FRAUENDORFER K., GLAVITSCH H., BACHER R., Optimization in Planning and Operation of Electric Power Systems, Physica-Verlag Heidelberg, 1993
[16] ANDERSSON J., A Survey of Multiobjective Optimization in Engineering Design, Technical Report: LiTH-IKP-R-1097, Linkoping University, www.jeo.org/emo/andersson00.pdf.gz
[17] BARQUIN J. et al, On the Cost of Reactive Power Generation and Voltage Support Service, Bulk Power System Dynamics and Control IV – Restructuring, Santorini, Greece, 1998
[18] MATPOWER, A MATLAB Power System Simulation Package, Available: http://www.pserc.cornell.edu/matpower
[19] GLAVIC M., WEHENKEL L., Interior Point Methods: A Tutorial Survey, Applications to Power Systems, and Research Opportunities, University of Liege, Belgium, 2004, http://www.montefiore.ulg.ac.be/~glavic/PIGAL-IPM-Report.pdf
[20] QUINTANA V. H., TORRES G. L., Introduction to Interior-Point Methods, IEEE PES task Force on Interior-Point Methods Applications to Power Systems, http://wathvdc3.uwaterloo.ca/~iee-ipm, 1997
[21] MATLAB Optimization Toolbox 3, Users Guide, The Math Works Inc., 2007
[22] ZHANG Y., Solving Large-scale Linear Programs by Interior-point Methods Under the MATLAB Environment, Optimization Methods and Software, 10(1998)
[23] Mrežna pravila elektroenergetskog sustava, Narodne Novine 36/2006

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KRITERIJI I METODA ODREĐIVANJA PRIORITETA ZA REVITALIZACIJU PRIJENOSNE MREŽE

THE CRITERIA AND METHOD OF DEFINING PRIORITIES FOR THE REVITALIZATION OF THE TRANSMISSION NETWORK

Davor Bajs – Matislav Majstrović, Zagreb, Hrvatska

U radu se razmatra problematika starenja jedinica prijenosne mreže i utjecaja starenja na pouzdanost elektroenergetskog sustava, te su postavljeni kriteriji i metodologija za izradu liste prioriteta za revitalizaciju vodova i transformatora u prijenosnim elektroenergetskim mrežama. Kriteriji za revitalizaciju temelje se na stvarnom stanju jedinice, te ulozi i važnosti jedinice unutar elektroenergetskog sustava. Probabilističkim simulacijama rada sustava i mult-iscenarijskom analizom izračunavaju se očekivani godišnji operativni troškovi rada sustava, a na temelju razlike tih troškova pri različitim razinama neraspoloživosti promatranih jedinica kvantificiraju se pojedini kriteriji ovisni o ulozi i važnosti jedinica, te se izračunava indeks važnosti kandidata za revitalizaciju. Na temelju tog indeksa, te indeksa stanja pojedinačnih kandidata za revitalizaciju, izrađuje se jedinstvena lista prioriteta vodova i transformatora za revitalizaciju.

The work examines the problem of the aging of transmission network units and the impact of it on the reliability of the electric power system (EPS). The criteria and methodology are defined for compiling a priority list for the revitalization of lines and transformers in transmission networks. The criteria are based on the real condition of a unit and the role and relevancy of the unit within the EPS. Through a probabilistic simulation and a multi-scenario analysis the expected annual operating costs of the system are calculated. Based on the difference of these costs at different unavailability levels of the observed units, the individual criteria, which are dependent on the role and relevance of the observed unit, are quantified and the significance index of the revitalization candidates is calculated. Based on that index, and the condition index of individual revitalization candidates, a single priority list of lines and transformers for revitalization is compiled.

Ključne riječi: lista prioriteta; pouzdanost elektroenergetskog sustava; revitalizacija; starenje jedinica prijenosne mreže
Keywords: priority list; reliability of the electric power system; revitalization; the aging of transmission network units

1 UVOD

Oprema i uređaji u elektroenergetskoj mreži troše se i stare za vrijeme svoje životne dobi. Svaki dio opreme ima svoje vlastito životno vrijeme unutar kojega se očekuje da će raditi u skladu s deklariranim karakteristikama bez većeg broja zastoja i kvarova. Funkcija neraspoloživosti ili broja kvarova jedinica (elemenata, uređaja) prijenosne mreže ima nepravilan oblik i ne može se matematički izraziti. U stvarnosti ona ima oblik tzv. kade, što znači da je karakterizira povećani broj kvarova (time i neraspoloživost) u početku korištenja jedinice nakon njenog puštanja u pogon, zatim dugačko razdoblje normalnog korištenja gdje je broj kvarova mali i približno konstantan, te na kraju razdoblja korištenja naglo povećani broj kvarova koji se događaju radi starosti promatrane jedinice.

U sustavu s većim brojem starih i dotrajalih jedinica čija je neraspoloživost povećana dolazi do narušavanja pouzdanosti, time i do smanjene sigurnosti opskrbe potrošača električnom energijom, odnosno povećanih troškova rada elektroenergetskog sustava u cjelini.

U ovom radu opisana je originalna metodologija i kriteriji na temelju kojih se mogu odrediti liste prioriteta za revitalizaciju vodova i transformatora u prijenosnim elektroenergetskim mrežama, s ciljem održavanja zadovoljavajuće sigurnosti pogona čitavog elektroenergetskog sustava (EES) i smanjenja operativnih troškova rada sustava.

2 OČEKIVANA ŽIVOTNA DOB JEDINICA MREŽE

Očekivanu životnu dob pojedinih jedinica mreže nije moguće unaprijed odrediti pa se stoga određuju očekivane veličine na temelju što većeg broja uzoraka istovrsnih jedinica. Iako se približavanje životnoj dobi može relativno sigurno predvidjeti na temelju pogonskih podataka i različitih terenskih i laboratorijskih ispitivanja opreme, uglavnom se promatraju grupe istovrsnih jedinica mreže te se definiraju približne veličine očekivane životne dobi dalekovoda (električki i građevinski dijelovi), kabela, transformatora, polja, ostale opreme u transformatorskim stanicama, sustava zaštite, telekomunikacija i sustava upravljanja te drugog.

Ukoliko se promatraju kvarovi električne opreme (uređaja, jedinica mreže) mogu se razlikovati dvije osnovne vrste kvarova prema njihovom uzroku: slučajni kvarovi – uzrokovani uglavnom vanjskim uzrocima, te kvarovi zbog starosti – uzrokovani promjenom karakteristika opreme tijekom njenog dugotrajnog korištenja. Osim te dvije vrste kvarova

1 INTRODUCTION

Equipment and devices in an electric power network are deteriorating and aging during their lifetime. Each equipment part has its own lifetime within which it is expected to operate in accordance with its declared characteristics without a greater number of outages and failures. The unavailability function or the number of failures on the units (elements, devices) of the transmission network is irregularly shaped and cannot be mathematically expressed. In reality it is bathtub-shaped, meaning that it is characterized by an increased number of failures (and thereby unavailability) in the initial period of using a unit after its commissioning, followed by a long span of normal use with a small and approximately constant number of failures, and, finally, a period of rapidly increasing number of failures occurring because of the age of the observed unit.

In a system having a greater number of old and deteriorated units with a higher level of unavailability, disrupted reliability begins to prevail and thereby reduced electricity supply security resulting in an increase in the operating costs of the EPS as a whole.

This work describes an original methodology and criteria on the basis of which priority lists for the revitalization of lines and transformers in transmission networks can be defined with an aim to keep a satisfactory level of operational security of the whole EPS and to reduce its operating costs.

2 LIFE EXPECTANCY OF NETWORK UNITS

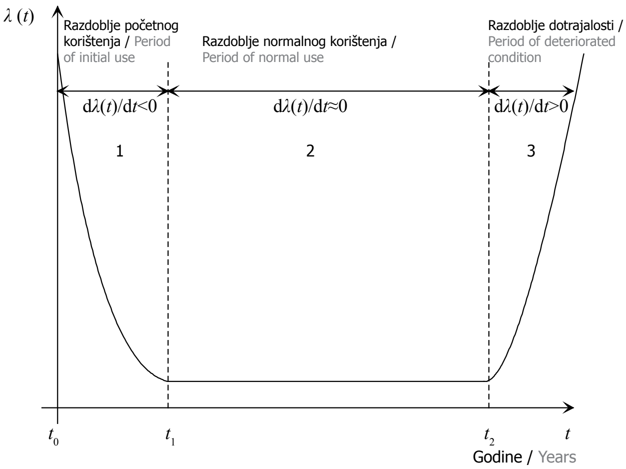
The life expectancy of individual network units cannot be defined beforehand, so expected values are defined on the basis of the greatest possible number of units of the same type. While the approaching end of the lifetime can be predicted with relative certainty, based on operation data and visual inspection and laboratory tests on conducted on equipment, mostly observed are the groups of network units of the same type so as to define the approximate life expectancy values of transmission lines (electrical and construction parts), cables, transformers, fields, other equipment in substations, protection systems, telecommunications, control systems and other.

Amongst the observed failures on electrical equipment (devices, network units) two basic types of failures by their cause can be distinguished: random failures – mostly caused by external influences and age-related failures – caused by changed equipment characteristics after a long use. In ad-postoje još i kvarovi uzrokovani manjkavom izvedbom opreme koji uglavnom dolaze do izražaja u početnoj fazi korištenja opreme. Nadalje, kvarovi električne opreme mogu se podijeliti na temelju mjesta nastanka uzroka kvara na vanjske i unutarnje kvarove, te na temelju mogućnosti saniranja kvara na popravljive i nepopravljive kvarove. Starenjem opreme u mreži dolazi do povećanog broja kvarova, time i do povećanog broja ispada, zastoja i neraspoloživosti jedinica mreže. Kako se oprema približava kraju svoje očekivane životne dobi aktivnosti i financijska sredstva koje je potrebno uložiti u njeno održavanje značajno se povećavaju.

Funkcija broja kvarova, neraspoloživosti ili intenziteta kvarova za električnu opremu ima poznati oblik kade (slika 1), te je nije moguće matematički formulirati za svaki pojedinačni slučaj.

dition to these two types of failures there are failures caused by poor construction, coming to the fore largely in the initial stage of equipment use. Furthermore, failures on electrical equipment can be divided by the place of their cause into external and internal ones, and, by their reparability, into reparable and unreparable ones. With the aging of equipment there is an increasing number of defects and thereby an increasing number of outages, failures and unavailability of network units. With the approaching end of the life expectancy of equipment, the funds to be spent on its maintenance tend to rise significantly.

The function of the number of failures, the unavailability or intensity of failures on electrical equipment is bathtub-shaped (Figure 1) and cannot be mathematically formulated for each particular case.



Slika 1 — Funkcija intenziteta kvara
Figure 1 — Defect intensity function

Unutar funkcije intenziteta kvarova razlikuju se tri područja vremena korištenja električne opreme:

- područje 1 između t_0 i t_1 – predstavlja razdoblje početnog korištenja, gdje nakon puštanja u pogon opreme dolazi do nastanka određenog broja kvarova. Kvarovi su uglavnom uzrokovani konstrukcijskim i dizajnerskim pogreškama pri izradi opreme. Funkcija intenziteta kvarova je padajuća $(\mathrm{d}\lambda(t)/\mathrm{d}t)<0$, jer sve kvarove otklanja proizvođač opreme radi garancije koja se traži,
- područje 2 između t_0 i t_1– predstavlja razdoblje normalnog korištenja gdje je intenzitet kvarova približno stalan, a kvarovi su uglavnom uzrokovani vanjskim utjecajem i slučajnog su karaktera. Funkcija intenziteta kvarova je približno konstantna $\mathrm{d}\lambda(t)/\mathrm{d}t \approx 0$,

Within the failure intensity function three areas of the use of electrical equipment can be distinguished:

- area 1 between t_0 and t_1 – represents the period of initial use, where after commissioning a certain number of failures occur. These failures are largely caused by structural and design errors during equipment manufacture. The failure intensity function is descending $(\mathrm{d}\lambda(t)/\mathrm{d}t)<0$, because all defects are corrected under the manufacturer's warranty,
- area 2 between t_1 and t_2 – represents the period of normal use, where the failure intensity is approximately constant and failures are largely caused by external influences and are of random nature. The failure intensity function is approximately constant $\mathrm{d}\lambda(t)/\mathrm{d}t \approx 0$,

— područje 3 nakon točke t_2 – predstavlja razdoblje dotrajalosti, gdje intenzitet kvarova naglo raste dok ne dostigne točku kada pogon više nije moguć. Funkcija intenziteta kvarova je rastuća $\mathrm{d}\lambda(t)/\mathrm{d}t > 0$. U tom su području dominantni kvarovi uzrokovani starošću opreme i značajno nadmašuju kvarove čiji su uzroci slučajnog karaktera.

Točka t_2 na slici 3 predstavlja vrijeme normalnog korištenja pojedine električne opreme, odnosno približno se može nazvati očekivanom životnom dobi. Nakon te točke razdoblje korištenja opreme moguće je produljivati uz smanjenu pouzdanost, odnosno raspoloživost jedinica, te povećana ulaganja u održavanje i popravke. Točku u vremenu, odnosno ograničeno vremensko razdoblje kada razdoblje normalnog korištenja prelazi u razdoblje dotrajalosti razlikuje se za svaku pojedinačnu opremu u mreži, te ovisi o nizu ostalih unutarnjih i vanjskih faktora, a nemoguće ju je sa sigurnošću predvidjeti. Idealno bi bilo revitalizaciju opreme, odnosno svake pojedinačne jedinice mreže provesti u trenutku t_2 ili neposredno nakon njega, čime bi se optimizirala financijska sredstva i razdoblje korištenja jedinice mreže.

Vrijeme prelaska iz razdoblja normalnog korištenja u razdoblje dotrajalosti za svaku pojedinačnu opremu/jedinicu u mreži ovisi o više faktora, kao što su: pogonskih uvjeta (opterećenja, naponi, kratki spojevi, broj sklopnih operacija i dr.), vanjskih utjecaja (klima, okoliš, izloženost atmosferskom onečišćenju itd.), izloženosti mehaničkom stresu, te izloženosti termičkom stresu.

Postoji više indikatora da se promatrana oprema nalazi na kraju razdoblja normalnog korištenja, odnosno očekivane životne dobi, kao što su: povećana neraspoloživost, povećani broj kvarova, povećani troškovi održavanja ili kraj razdoblja korištenja istovrsne opreme u mreži. Izuzev kraja životne dobi pojedinih jedinica mreže radi starosti, trajni izlazak iz pogona i zamjena pojedinih jedinica također može biti uzrokovana drugim razlozima strateške, ekonomske ili tehničke naravi.

Procjene očekivane životne dobi električkih komponenata nadzemnih vodova u dostupnoj literaturi kreću se između 40 i 60 godina. Pri tom se pojedine komponente (izolatorski članci, dijelovi ovjesne i spojne opreme, pojedine dionice vodiča i zaštitne užadi) parcijalno zamjenjuju tijekom eksploatacije dalekovoda. U [1] definirana je prosječna vrijednost očekivane životne dobi Al/Č vodiča od 54 godine, s odstupanjem od ±14 godina, te čelično-rešetkastih stupova od 63 godine ± 21 godinu. Pravi se razlika između vodova koji se nalaze unutar normalnog okruženja, te vodova koji se nalaze unutar izrazito zagađenog područja, čija očekivana životna dob električkih komponenata

— area 3 after point t_2 – represents the period of deteriorated condition, where the failure intensity rapidly grows until reaching a point where operation is no longer possible. The failure intensity function is ascending $\mathrm{d}\lambda(t)/\mathrm{d}t > 0$. In that area the dominant failures are caused by the age of equipment and significantly exceed the failures caused by random factors.

Point t_2 in Figure 3 represents the time of normal use of an electrical equipment, and can be approximately attributed to life expectancy. After that point the period of equipment use can be prolonged with reduced reliability/availability of units and increased spending on maintenance and repair. The point in time, or the limited period of time when the period of normal use passes into the period of deteriorated condition, differs from equipment to equipment in the network, depending on a variety of other internal and external factors, and cannot be predicted with any fair amount of certainty. The revitalization of equipment or each particular network unit would be ideal to carry out in moment t_2 or immediately thereafter, whereby the finances and the period of using the network unit would be optimized.

The time of transition from the period of normal use to the period of deteriorated condition for each particular equipment/network unit depends on a number of factors, such as operation conditions (loads, voltages, short-circuits, number of switching operations, etc.), external influences (weather, environment, exposure to atmospheric pollution, etc.), exposure to mechanical stress and thermal stress.

There is a number of indications that the observed equipment has reached the end of normal use or life expectancy, such as: greater unavailability, increased number of failures, higher maintenance costs or the end of using the same type of equipment in network. Apart from the end of the lifetime of certain network units as a result of age, permanently discontinued operation and replacement of individual units can also be caused by other reasons of strategic, economic or technical nature.

The assessments of the life expectancy of the electrical components of overhead lines in accessible literature vary between 40 and 60 years. Some transmission line components (insulators, parts of suspension and couplings, some conductor sections and protective wire) are partially replaced during the exploitation of the transmission line. Literature [1] estimates the average value of an ACSR conductor at 54 years with a deviation of ±14 years, and of steel towers at 63 years ± 21 years. A distinction is made between the lines in a normal environment and those in an excessively polluted environment where the life expectancy of electrical iznosi 46 godina ± 15 godina. Prema [2] očekivana životna dob za stupove dalekovoda iznosi između 50 godina i 70 godina, a 35 godina do 50 godina za vodiče, izolaciju, te nosnu i spojnu opremu.

Prema dosadašnjim iskustvima u pogonu visokonaponskih kabela i raspoloživih tehničkih podataka očekivana životna dob za uljne kabele iznosi oko 50 godina [2]. Za određivanje povoljnog trenutka zamjene ovu vrijednost moguće je korigirati ovisno o opterećenju kabela (sadašnjem i očekivanom), zabilježenim pogonskim događajima i uvjetima u kojima je kabel položen. Očekivana životna dob ostalih vrsta procjenjuje se u suradnji s proizvođačima. Prema [1] očekivana životna dob za uljne kabele iznosi 52 godine, s odstupanjem od ±20 godina.

Na pravo stanje energetskih transformatora točnu informaciju, na temelju koje se može donijeti odluka o revitalizaciji, može dati jedino potpuna analiza pogonskih događaja, te dijagnosticiranje njihovog stanja. Zbog visokih investicijskih troškova velikih energetskih transformatora njihova je zamjena određena starošću, odnosno oni ostaju u pogonu sve dok je to tehnički moguće. Ekonomski razlozi za zamjenu poput smanjenja gubitaka unutar transformatora gotovo nikad nisu motiv za zamjenu. Veći popravci ostarjelih transformatora također se gotovo nikad ne prakticiraju budući da su troškovi popravaka visoki. Važni faktori koji utječu na karakteristike transformatora su vlaga i kisik. Povećanjem sadržaja vlage u ulju smanjuje se njegova probojna čvrstoća. Vlaga također može oštetiti čvrstu (papirnatu) izolaciju namotaja transformatora, kao i kisik i toplina [3] i [4]. Generalno se može zaključiti da na starenje transformatora glavni utjecaj imaju vlaga, toplina i kisik, najviše ovisni o pogonskim uvjetima kojima je transformator izložen u vremenu njegova korištenja. Očekivana se životna dob velikih energetskih transformatora prema dostupnim procjenama kreće između 42 godine [1] i 50 godina [5], uz pretpostavku njihovog redovitog održavanja i nepostojanja većih kvarova koji bi ga trajno oštetili.

3 PROCJENA BUDUĆE NERASPOLOŽIVOSTI JEDINICA MREŽE

3.1 Promatrane jedinice prijenosne mreže

Prijenosnu mrežu sačinjava čitav niz različitih objekata i uređaja, odnosno jedinica, komponenta i elemenata. Najvažniji su: nadzemni vodovi, kabelski vodovi, transformatorske stanice zajedno s transformatorima i poljima te ostalom opremom, zaštitni uređaji, mjerni uređaji, telekomunikacij-

components is 46 years ± 15 years. According to [2], life expectancy varies between 50 and 70 years for transmission line towers, and between 35 years and 50 years for conductors, insulators, suspension and couplings.

According to experiences gained so far in the operation of high-voltage cables and available technical data, the life expectancy of oil cables is around 50 years [2]. For assessing the favorable replacement timing, this value can be corrected in dependence on the cable load (present and expected), recorded operation events and conditions under which the cable is laid. The life expectancy of other types is assessed in conjunction with the manufacturers. According to [1], life expectancy of oil cables is 52 years with a deviation of ±20 years.

It is only a comprehensive analysis of operation events and their diagnosis that can provide accurate information about the real condition of power transformers, based on which a decision on revitalization can be made. Due to the high cost of investment in large power transformers, their replacement is determined by age, in other words, they remain in operation as long as technically possible. The economic reasons for their replacement, such as reduction of losses within the transformers, are virtually never a motivation strong enough to undertake replacement. Major repair works on old transformers are, due to high costs of such repairs, virtually never practiced either. Important factors influencing the characteristics of transformers are humidity and oxygen. Increased humidity content in oil reduces their breakdown strength. Humidity can also impair the solid (paper) insulation of transformer windings, as can oxygen and heat, [3] and [4]. Generally, the main influence on the aging of transformers is exerted by humidity, heat and oxygen, which depends above all on operation conditions to which a transformer has been exposed during its use. The life expectancy of a large power transformers, judging by available estimates, varies between 42 [1] and 50 years [5], provided that it is regularly serviced and spared from major defects that would leave a permanent damage.

3 ASSESSING THE FUTURE UNAVAILABILITY OF NETWORK UNITS

3.1 Observed transmission network units

A transmission network consists of a series of various facilities and devices, or units, components and elements, the most important among them being: overhead lines, cables, substations together with transformers and fields and other equipment, protective devices, measuring devices, telecomska mreža i telekomunikacijska oprema, sustavi vođenja i dr.

Ovaj rad odnosi se na kapitalne jedinice prijenosne mreže, odnosno vodove i transformatore. Promatranje ne ide dublje u podjelu na komponente i pojedine dijelove, već se isti promatraju unutar cjeline, odnosno jedinice mreže.

3.2 Zastoji u prijenosnoj mreži

Najčešće korišteni pokazatelj pouzdanosti prijenosne mreže je njena raspoloživost, odnosno neraspoloživost. Neraspoloživost se definira kao vremenski period unutar promatranog vremenskog razdoblja (najčešće godina dana) unutar kojega mreža, odnosno neka njena jedinica, nije u funkciji.

Poremećaj se definira kao spontano zbivanje u promatranoj mreži u kojem je došlo do prisilnog isklopa barem jednog prekidača, odnosno do prisilnog zastoja barem jedne jedinice prijenosne mreže. Poremećaj započinje kvarom, odnosno događajem kojim neka jedinica prelazi iz ispravnog u neispravno stanje. Otkaz ili ispad definira se kao događaj kojim neka jedinica prisilno prelazi iz pogonskog u izvan pogonsko stanje. Prisilni zastoj je izvan pogonsko stanje promatrane jedinice ostvareno ispadom ili prisilnim isklopom, a neplaniranim ili pogonskim isklopom [6]. S obzirom na uzroke prisilnih zastoja razlikuju se dvije grupe zastoja:

- prisilni zastoj radi unutarnjeg razloga – zastoj radi vlastite neispravnosti,
- prisilni zastoj radi vanjskog razloga – zastoj radi djelovanja zaštite ili isklopom.

Ukoliko je promatrana jedinica u prisilnom zastoju radi vlastite neispravnosti, razlikuje se prisilni zastoj radi unutarnjeg razloga. Ispravna jedinica može biti u prisilnom zastoju ukoliko je izvan pogona radi djelovanja zaštite ili isklopom pa se govori o prisilnom zastoju s vanjskim razlogom. Prisilni zastoj može biti trajan, privremen ili prolazan.

Trajan prisilni zastoj je onaj zastoj koji nastaje radi kvara komponente ili elementa jedinice, nakon čega jedinica nastavlja pogon po otklanjanju kvara. Privremen prisilni zastoj je onaj zastoj kod kojega jedinica nastavlja pogon nakon njenog isklopa bez popravka ili zamjene neke od njezinih komponenata, dok je prolazan prisilni zastoj onaj zastoj kada jedinica nastavlja pogon nakon njenog isklapanja i uspješnog djelovanja APU (automatskog ponovnog uklapanja). Očito je da će starost jedinice imati utjecaj jedino na veličinu trajnih prisilnih zastoja, dok će se privremeni i prolazni prisilni zastoji događati neovisno o starosti promatrane jedinice.

munication network and equipment, control systems, etc.

This work deals with the capital units of a transmission network, i.e., lines and transformers. They are not examined in depth in terms of division into components and parts, they are examined instead within a whole, as network units.

3.2 Outages in the transmission network

The most frequently used indicator of the reliability of a transmission network is its availability and unavailability respectively. Unavailability is defined as a time interval within the observed period of time (mostly one year) when a network or one of its units is out of operation.

Disruption is defined as a spontaneous event within the observed network when a forced disconnection occurs on at least one circuit breaker, or a forced outage of at least one unit of the transmission line. A disruption starts with a failure, an event where a unit passes from a correct into a faulty state. An outage is defined as an event where a unit forcibly passes from an operable into an inoperable state. A forced outage is the out-of-operation condition of the observed unit resulting from sudden outage or forced disconnection, not planned or done intentional [6]. In terms of the causes there are two groups of forced outages:

- forced outage caused by internal reason – outage due to own faultiness,
- forced outage caused by external reason – outage due to a protective action or disconnection.

If the observed unit is in the state of forced outage due to its own faultiness, it is a case of an internal reason. A functional unit may be in the state of forced outage if out of operation due to a protective action or disconnection, so this is a case of a forced outage for an external reason. A forced outage can be permanent, temporary or transient.

A permanent forced outage is one caused by a defective component or element of the unit, after which the unit resumes operation once the defect has been corrected. A temporary forced outage is one where the unit resumes operation after its disconnection without repair or replacement of one of its components. A transient forced outage is one where the unit resumes operation after its disconnection and successful automatic re-closure. It is obvious that the age of the unit will influence only the extent of permanent forced outages, whereas the temporary and transient forced outages will occur aside from the age of the observed unit.

Planirani zastoj je izvan pogonsko stanje promatrane jedinice ostvareno smišljeno, planiranim isklopom, a ne ispadom, radi provođenja neke planirane namjere poput provođenja plana održavanja, otklanjanja nedostataka, preventivne dijagnostike i sličnog [6]. S obzirom na uzroke planiranih zastoja također se razlikuju dvije grupe zastoja:

- planirani zastoj radi unutarnjeg razloga – zastoj radi zahvata na promatranoj jedinici,
- planirani zastoj radi vanjskog razloga – zastoj radi zahvata izvan promatrane jedinice.

Planirani zastoj radi unutarnjeg razloga nastaje ukoliko dolazi do zahvata na promatranoj jedinici, dok planirani zastoj radi vanjskog razloga nastaje ukoliko dolazi do zahvata izvan promatrane jedinice, ali je promatranu jedinicu zbog tog zahvata nužno isključiti.

Starost pojedine jedinice prijenosne mreže utječe i na prisilne i na planirane zastoje, no samo na one s unutarnjim razlogom. Vanjski razlozi za prisilne i planirane zastoje jedinica prijenosne mreže događaju se neovisno o njihovoj starosti, odnosno pogađaju jednakom vjerojatnošću i starije i novije jedinice mreže. Radi starosti jedinice može se očekivati povećani broj prisilnih zastoja radi vlastite neispravnosti jedinice, ali i povećani broj planiranih zastoja s unutarnjim razlogom radi povećanih aktivnosti na održavanju jedinice, otklanjanju nedostataka, dijagnostici i drugom.

Ukoliko se ukupnu neraspoloživost neke jedinice prijenosne mreže označi sa q vrijedi sljedeća relacija:

A planned outage is an out-of-operation state of the observed unit brought about deliberately through planned disconnection, not a breakdown, in order to carry out some planned works, such as implementation of a maintenance schedule, rectification of deficiencies, preventive diagnostics, and similar [6]. In terms of their causes there are two groups of forced outages:

- planned outage caused by internal reason – remedial action on the observed unit,
- planned outage caused by external reason – remedial action outside of the observed unit.

A planned outage caused by internal reason is intended to take a remedial action on the observed unit, whereas a planned outage caused by external reason is undertaken if a remedial action is to take place outside of the observed unit which must be disconnected for that purpose.

The age of a transmission network unit also influences both the forced and the planned outages, but only those with an internal reason. External reasons for forced and planned outages of transmission network units occur aside from their age, and they affect both older and newer network units with equal probability. As a result of the age of a unit an increased number of forced outages can be expected because of the unit's own faultiness, but also an increased number of planned outages for an internal reason, those caused by intensified activities involving maintenance, rectification of deficiencies, diagnostics and other works on the unit.

If the total unavailability of a transmission network unit is marked q, the following relation applies:

$$q = q_{\mathrm{pr}} + q_{\mathrm{pl}} \,, \tag{1}$$

gdje su:

q_{pr} – neraspoloživost radi prisilnih zastoja, a
q_{pl} – neraspoloživost radi planiranih zastoja.

Nadalje vrijedi sljedeće:

where:

q_{pr} – unavailability due to forced outages, and
q_{pl} – unavailability due to planned outages.

Furthermore, the following applies:

$$q_{\mathrm{pr}} = q_{\mathrm{pr\_un}} + q_{\mathrm{pr\_va}} \,, \tag{2}$$

$$q_{\mathrm{pr\_un}} = q_{\mathrm{pr\_un-tr}} + q_{\mathrm{pr\_un-pr}} \,, \tag{3}$$

$$q_{\mathrm{pl}} = q_{\mathrm{pl\_un}} + q_{\mathrm{pl\_va}} \,, \tag{4}$$

$$q = q_{\mathrm{pr\_u}n} + q_{\mathrm{pr\_va}} + q_{\mathrm{pl\_un}} + q_{\mathrm{pl\_va}} \,, \tag{5}$$

gdje su:

q_{pr_un} – neraspoloživost radi prisilnih zastoja s unutarnjim razlogom,
$q_{pr\_un\text{-}tr}$ – neraspoloživost radi trajnih prisilnih zastoja s unutarnjim razlogom,
$q_{pr\_un\text{-}p}$ – neraspoloživost radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom,
q_{pl_va} – neraspoloživost radi prisilnih zastoja s vanjskim razlogom,
q_{pl_un} – neraspoloživost radi planiranih zastoja s unutarnjim razlogom.

Moguće je generalno utvrditi da starost promatrane jedinice prijenosne mreže utječe na veličine $q_{pr\_un\text{-}r}$ i q_{pl_un}. Budući da se u prisilne zastoje radi unutarnjeg razloga ubrajaju i oni zastoji koji nastaju radi pogonskih prilika i preopterećenja pojedinih jedinica mreže (koja ne ovise o njihovoj starosti), te da se u planirane zastoje radi unutarnjeg razloga ubrajaju i oni zastoji radi redovitog održavanja ili preventivne dijagnostike koji ne trebaju nužno biti povezani sa starošću jedinice u zastoju, teško je naći točnu funkcionalnu ovisnost ove dvije veličine o starosti promatrane jedinice.

Gornja podjela prisilnih i planiranih zastoja koji čine ukupnu neraspoloživost jedinica izvršena je s ciljem procjene buduće neraspoloživosti starijih jedinica mreže, a detaljnom statističkom obradom pogonskih događaja moguće je kvantificirati sve veličine prisilnih i planiranih zastoja te ih razvrstati prema unutarnjim i vanjskim razlozima. Nakon registracije događaja, odnosno ispada neke jedinice ili njenog namjernog isključenja, te identifikacije uzroka tog ispada ili isključenja, moguće je odrediti da li se radi o prisilnom ili planiranom zastoju, je li uzrok zastoju unutarnji ili vanjski, te u slučaju unutarnjeg razloga da li se radi o trajnom ili prolaznom ili privremenom kvaru jedne ili više komponenti.

3.3 Funkcije razdiobe i vjerojatnost zastoja

Zastoji jedinica prijenosne mreže mogu se smatrati slučajnim događajima kojima se pridružuje određena vjerojatnost. Promatraju se jedinice prijenosne mreže i njihova obilježja vezana za prisilne i planirane zastoje te njihove uzroke.

Svakom od tih obilježja može se pridružiti određena vjerojatnost $P(x)$ te pretpostaviti njihove kontinuirane razdiobe na temelju nekih teoretskih distribucija.

Tablica 1 prikazuje jedinice promatranja (jedinice prijenosne mreže), njihova promatrana obilježja (neraspoloživosti radi različitih vrsta zastoja), slučajne varijable te pridružene funkcije vjero-

where:

q_{pr_un} – unavailability due to forced outages caused by internal reason,
$q_{pr\_un\text{-}tr}$ – unavailability due to permanent forced outages caused byinternal reason,
$q_{pr\_un\text{-}p}$ – unavailability due to temporary and transient forced outages caused by internal reason,
q_{pl_va} – unavailability due to forced outages caused by external reason,
q_{pl_un} – unavailability due to planned outrages caused by internal reason.

It can be generally ascertained that the age of an observed transmission network unit influences the values $q_{pr\_un\text{-}r}$ and q_{pl_un}. Considering the fact that as forced outages due to an internal reason are also counted the outages caused by operation conditions and overload of some network units (not linked to their age) and that as planned outages for an internal reason are also counted the outages caused by regular maintenance or preventive diagnostics which may not be necessarily linked to the age of the disabled unit, it is hard to find the exact functional dependence of these two values on the age of the observed unit.

The above distribution of the forced and planned outages constituting the overall unavailability of units has been made with a view to assessing the future unavailability of older network units. By detailed statistical processing it is possible to quantify all the values of forced and planned outages and classify them by internal and external causes. Once an event of outage or intentional switching-off of a unit is taken note of and its cause identified, it is possible to determine whether it is a forced or planned outage, whether the cause is internal or external and, if internal, whether it is a case of a permanent or temporary or transient failure on one or more components.

3.3 Distribution functions and the probability of an outage

The outages of transmission network units can be viewed as contingent events accompanied by a certain amount of probability. The units of a transmission network are observed and so are their features associated with forced and planned outages and their causes.

To each of these features a certain probability $P(x)$ is attributable, and, based on some theoretical distributions, their continuous distributions can be presumed.

Table 1 shows the units of observation (transmission network units), their observed features (unavailabilities due to various outages), random variables, jatnosti i razdiobe slučajne varijable. Na temelju statistike pogonskih događaja moguće je odrediti osnovne parametre funkcija razdiobe slučajnih varijabli, i to:

- aritmetičku sredinu $\overline{x}_i$,
- standardnu devijaciju σ_i,

te na temelju tih dviju veličina i ostale parametre traženih funkcija.

associated probability functions and random variable distributions. Based on the statistics of operation events, it is possible to define the basic parameters of the random variable distribution functions, viz.:

- arithmetic mean $\overline{x}_i$,
- standard deviation σ_i,

and, based on these two values, define the other parameters of the related functions.

Tablica 1 – Zastoji jedinica prijenosne mreže, funkcije vjerojatnosti i funkcije razdiobe
Table 1 – Outages of transmission network units, probability functions and distribution functions

Jedinica promatranja / Observed unit	Obilježje jedinice / Unit feature	Slučajna varijabla / Random variable	Funkcija vjerojatnosti / Probability function	Funkcija razdiobe slučajne varijable / Random variable distribution function
Nadzemni vod / Overhead line Kabel / Cable Transformator / Transformer	Neraspoloživost radi trajnih prisilnih zastoja s unutarnjim razlogom / Unavailability due to permanent forced outages caused by internal reason	$q_{\text{pr\_un-tr}}$	$P(q_{\text{pr\_un-tr}})$	$F(q_{\text{pr\_un-tr}})$
	Neraspoloživost radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom / Unavailability due to temporary and transient forced outages caused by internal reason	$q_{\text{pr\_un-pr}}$	$P(q_{\text{pr\_un-pr}})$	$F(q_{\text{pr\_un-pr}})$
	Neraspoloživost radi prisilnih zastoja s vanjskim razlogom / Unavailability due to forced outages caused by external reason	$q_{\text{pr\_va}}$	$P(q_{\text{pr\_va}})$	$F(q_{\text{pr\_va}})$
	Neraspoloživost radi planiranih zastoja s unutarnjim razlogom / Unavailability due to planned outages caused by internal reason	$q_{\text{pl\_un}}$	$P(q_{\text{pl\_un}})$	$F(q_{\text{pl\_un}})$
	Neraspoloživost radi planiranih zastoja s vanjskim razlogom / Unavailability due to planned outages caused by external reason	$q_{\text{pl\_va}}$	$P(q_{\text{pl\_va}})$	$F(q_{\text{pl\_va}})$

U teoriji pouzdanosti mreža najčešće korištene teoretske funkcije vjerojatnosti i funkcije razdiobe slučajne varijable su normalna razdioba i Weibullova razdioba [7]. Normalna razdioba određena je aritmetičkom sredinom i standardnom devijacijom (6), dok je Weibullova razdioba (7) određena parametrima oblika i mjere (k i λ) koje je također moguće odrediti na temelju poznate aritmetičke sredine i standardne devijacije [8]:

In the theory of network reliability the most often used theoretical probability functions and random variable distribution functions are the normal distribution and the Weibull distribution [7]. The normal distribution is defined by the arithmetic mean and the standard deviation (6), whereas the Weibull distribution (7) is defined by the shape and scale (k and λ) parameters which can also be defined on the basis of a known arithmetic mean and standard deviation [8]:

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{\frac{-(x-\overline{x})^2}{2\sigma^2}} , \tag{6}$$

$$F(x,k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} \mathrm{e}^{-(\frac{x}{\lambda})^k} . \tag{7}$$

3.3 Metoda za procjenu neraspoloživosti jedinica mreže u kratkoročnom razdoblju

Kako je prethodno objašnjeno nije moguće univerzalno i jednoznačno naći funkcionalnu ovisnost neraspoloživosti jedinica prijenosne mreže i njihove starosti. U razdoblju normalnog korištenja jedinice njena neraspoloživost je približno konstantna, odnosno ne ovisi o starosti promatrane jedinice. Unutar razdoblja dotrajalosti funkcionalna ovisnost može biti snažna budući da se neraspoloživost jedinice značajno povećava s njenom starosti, ali ju je i dalje nemoguće jednoznačno odrediti.

Definirana metoda za procjenu buduće neraspoloživosti jedinica prijenosne mreže temelji se na podacima o zastojima jedinica i njihovim uzrocima iz statistike pogonskih događaja, te određivanju vjerojatnosti zastoja u promatranom budućem kratkoročnom razdoblju pretpostavljajući da se određene vrste zastoja (funkcionalno ovisne o starosti promatrane jedinice) distribuiraju na temelju poznatih teoretskih funkcija razdiobe slučajne varijable (normalna razdioba i Weibull-ova razdioba).

Procjena kratkoročne neraspoloživosti promatranih jedinica prijenosne mreže (vodova i transformatora) vrši se na sljedeći način:

— za vodove i transformatore mlađe od 40 godina (ili neke druge postavljene granice) pretpostavlja se konstantna neraspoloživost radi prisilnih i planiranih zastoja, te konstantna ukupna neraspoloživost, jednaka odgovarajućim prosjecima (aritmetičkim sredinama) za razdoblje obuhvaćeno statistikom pogonskih događaja:

3.3 Method of estimating the unavailability of network units in a short-term period

As explained above, there is no universal and clear-cut way of finding the functional dependence of the unavailability of transmission network units and their age. In a period of normal use the unavailability of a unit is approximately constant in that it does not depend on the age of the observed unit. Within a period of deteriorated condition the functional dependence may be strong because the unavailability of a unit is significantly increasing with its age, but it continues to defy a clear-cut definition.

The defined method of estimating the future unavailability of transmission network units is based on data concerning the outages of the units and their causes taken from the statistics on operation events and on the definition of outage probability in the observed future short-term period, provided that certain types of outages (functionally dependent on the age of the observed unit) are distributed in conformity with the known theoretical random variable distribution functions (the normal distribution and the Weibull distribution).

The short-term unavailability of observed transmission network units (lines and transformers) is assessed as follows:

— for lines and transformers younger than 40 years (or some other set limit) a constant unavailability is assumed due to forced and planned outages, as well as constant overall unavailability, equal to the corresponding averages (arithmetic means) for a period covered by the statistics of operation events:

$$q_{\mathrm{pr}} = \frac{1}{N} \cdot \sum_{n=1}^{N} q_{\mathrm{pr},n} \ , \qquad (8)$$

$$q_{\mathrm{pl}} = \frac{1}{N} \cdot \sum_{n=1}^{N} q_{\mathrm{pl},n} \ , \qquad (9)$$

gdje je:

N – ukupan broj godina obuhvaćenih statistikom pogonskih događaja,
$q_{\mathrm{pr},n}$ – neraspoloživost radi prisilnih zastoja u n-toj godini promatranja, a
$q_{\mathrm{pl},n}$ – neraspoloživost radi planiranih zastoja u n-toj godini promatranja.

Za ovu grupu promatranih jedinica prijenosne mreže ne razlikuju se prisilni i planirani zastoji radi unutarnjih i vanjskih razloga, tako ni prisilni

where:

N – total number of years covered by the statistics of operation events,
$q_{\mathrm{pr},n}$ – unavailability due to forced outages in the n-th observation year, and
$q_{\mathrm{pl},n}$ – unavailability due to planned outages in the n-th observation year.

For this group of observed transmission network units there is no difference between the forced and the planned outages due to internal and external zastoji radi unutarnjih razloga prema istrajnosti (trajni, prolazni, privremeni), budući da se pretpostavlja kako se isti nalaze u razdoblju normalnog korištenja kada nije vidljiva funkcionalna veza između određenih vrsti zastoja i starosti jedinice mreže.

— za kandidate starije od 40 godina u promatranom trenutku pretpostavlja se sljedeće:

    - u razmatranom kratkoročnom razdoblju neće doći do trajnog isključenja niti jedne promatrane jedinice mreže (nije trajan kvar, odnosno uništenje),
    - starost jedinice ima posljedice samo na prisilne i planirane zastoje radi unutarnjih razloga, a unutar prisilnih zastoja radi unutarnjih razloga samo na trajne prisilne zastoje,
    - prisilni i planirani zastoji radi vanjskih razloga, te prolazni i privremeni prisilni zastoji radi unutarnjih razloga, ne ovise o starosti promatrane jedinice,
    - neraspoloživosti jedinice zbog trajnih prisilnih i planiranih zastoja radi unutarnjih razloga opisuju se svaka svojom funkcijom razdiobe (normalne ili Weibullove),
    - srednje vrijednosti i standardne devijacije uzorka neraspoloživosti jedinica zbog trajnih prisilnih i planiranih zastoja s unutarnjim razlogom u razdoblju obuhvaćenom statistikom pogonskih događaja definiraju funkciju normalne razdiobe ili funkciju Weibullove razdiobe na temelju koje se procjenjuje kratkoročna neraspoloživost jedinica zbog trajnih prisilnih zastoja radi unutarnjih razloga i neraspoloživost jedinica zbog planiranih zastoja radi unutarnjih razloga,
    - postavlja se vjerojatnost od 0,95 da će procijenjene vrijednosti neraspoloživosti radi trajnih prisilnih i planiranih zastoja s unutarnjim razlogom poprimiti vrijednosti u intervalu od 0 do procijenjene vrijednosti neraspoloživosti, a iz razloga sigurnosti za procijenjenu vrijednost neraspoloživosti radi trajnih prisilnih i planiranih zastoja s unutarnjim razlogom uzimamo gornju granicu intervala,
    - procijenjene buduće neraspoloživosti radi prolaznih i privremenih prisilnih zastoja s unutarnjim razlogom, te prisilnih i planiranih zastoja s vanjskim razlogom, jednake su srednjoj vrijednosti uzorka istovrsnih neraspoloživosti iz statistike pogonskih događaja.

Neraspoloživosti radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom ($q_{\mathrm{pr\_un\text{-}p}}$), neraspoloživosti radi prisilnih zastoja s vanjskim razlogom ($q_{\mathrm{pr\_va}}$) i neraspoloživosti radi planiranih

reasons, nor the forced outages for internal reasons according to the degree of persistence (permanent, transient, temporary), since it is assumed that they take place in the periods of normal use when the functional link between certain types of outages and the age of a network unit is not obvious.

— For candidates older than 40 years at an observed juncture the following is presumed:

    - over the observed short-term period there will be no permanent disconnection of any observed network unit (it is not a permanent defect or a destruction),
    - the age of the unit concerned has affects only the forced and planned outages caused by internal reasons, and within the forced outages caused by internal reasons only the permanent forced outages,
    - the forced and planned outages caused by external reasons, and the transient and temporary forced outages caused by internal reasons, are independent of the age of the observed unit,
    - the unavailabilities of a unit due to permanent forced and planned outages caused by internal reasons are each described with its distribution function (normal or Weibull),
    - the mean values and standard deviations of an unavailability sample of units due to permanent forced and planned outages caused by internal reason in the period covered by the statistics of operation events define the normal distribution function or the Weibull distribution function, on the basis of which the short-term unavailability of units due to permanent forced outages caused by internal reasons and the unavailability of units due to planned outages caused by internal reasons are assessed,
    - a probability of 0.95 is set that the assessed unavailability values due to permanent forced and planned outages caused by internal reason will assume values in an interval from 0 to the assessed unavailability value, whereas, to be on the safe side, for the assessed unavailability value due to permanent forced and planned outages caused by internal reason the upper limit of the interval is taken
    - the assessed future unavailabilities due to transient and temporary forced outages caused by internal reason, and forced and planned outages caused by external reason, equal the mean value of the sample of unavailabilities of the same type taken from the statistics of operation events.

The unavailabilities due to temporary and transient forced outages caused by internal reason ($q_{\mathrm{pr\_un\text{-}p}}$), the unavailabilities due to forced outages caused by zastoja s vanjskim razlogom ($q_{\mathrm{pl\_va}}$) ne ovise o starosti voda pa se računaju kao:

external reason ($q_{\mathrm{pr\_va}}$) and the unavailabilities due to planned outages caused by external reason ($q_{\mathrm{pl\_va}}$) are independent of the age of the line, so they are calculated as:

$$q_{\mathrm{pr\_un-pr}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pr\_un-pr},n} \quad , \tag{10}$$

$$q_{\mathrm{pr\_va}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pr\_va},n} \quad , \tag{11}$$

$$q_{\mathrm{pl\_va}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pl\_va},n} \quad , \tag{12}$$

gdje je:

$q_{\mathrm{pr\_un-pr},n}$ – neraspoloživost radi privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom u godini n,

$q_{\mathrm{pr\_va},n}$ – neraspoloživost radi prisilnih zastoja s vanjskim razlogom u godini n,

$q_{\mathrm{pl\_va},n}$ – neraspoloživost radi planiranih zastoja s vanjskim razlogom u godini n, te ostaju konstantne za promatrano buduće razdoblje.

Srednje vrijednosti neraspoloživosti radi trajnih prisilnih i planiranih zastoja radi unutarnjih razloga iznose:

where:

$q_{\mathrm{pr\_un-pr},n}$ – unavailability due to temporary and transient forced outages caused by internal reason in year n,

$q_{\mathrm{pr\_va},n}$ – unavailability due to forced outages caused by external reason in year n,

$q_{\mathrm{pl\_va},n}$ – unavailability due to planned outages caused by external reason in year n, remaining constant for the observed future period.

The mean values of unavailability due to permanent forced and planned outages caused by internal reasons amount to:

$$q_{\mathrm{pr\_un-}tr} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pr\_un-tr},n} \quad , \tag{13}$$

$$q_{\mathrm{pl\_un}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pl\_un},n} \quad , \tag{14}$$

gdje je:

$q_{\mathrm{pr\_un-tr},n}$ – neraspoloživost radi trajnih prisilnih zastoja s unutarnjim razlogom u godini n,

$q_{\mathrm{pl\_un},n}$ – neraspoloživost radi planiranih zastoja s unutarnjim razlogom u godini n.

Standardne devijacije neraspoloživosti radi prisilnih i planiranih zastoja s unutarnjim razlogom iznose:

where:

$q_{\mathrm{pr\_un-tr},n}$ – unavailability due to permanent forced outages caused byinternal reason in year n,

$q_{\mathrm{pl\_un},n}$ – unavailability due to planned outages caused byinternal reason in year n.

Standard deviations of unavailability due to forced and planned outages caused by internal reason amount to:

$$\sigma_{\mathrm{pr\_un-tr}} = \sqrt{\frac{\sum_{n=1}^{n=N} (q_{\mathrm{pr\_un-tr},n} - q_{\mathrm{pr\_un-tr}})^2}{(N-1)}} \, , \tag{15}$$

$$\sigma_{\mathrm{pl\_un}} = \sqrt{\frac{\sum_{n=1}^{n=N} (q_{\mathrm{pl\_un},n} - q_{\mathrm{pl\_un}})^2}{(N-1)}} \, , \tag{16}$$

gdje je N veličina uzorka (broj godina obuhvaćenih statistikom pogonskih događaja).

Funkcija normalne razdiobe definirana je izrazom (6), dok je vjerojatnost da varijabla x poprimi neku vrijednost iz intervala $[x_1, x_2]$ definirana sljedećim izrazom:

where N is the sample size (number of years covered by the statistics of operation events).

The normal distribution function is defined by the expression (6), whereas the probability of variable x to assume some value from the interval $[x_1, x_2]$ is defined by the following expression:

$$P(x_1 < x < x_2) = \int_{x_1}^{x_2} F(x) \cdot \mathrm{d}\,x = \int_{x_1}^{x_2} \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{\frac{-(x-\bar{x})^2}{2\sigma^2}} \cdot \mathrm{d}\,x \, . \tag{17}$$

Kod Weibullove razdiobe funkcija razdiobe definirana je izrazom (7), a vjerojatnost da varijabla x poprimi vrijednost iz intervala $[x_1, x_2]$ računa se preko sljedećeg izraza:

With the Weibull distribution the distribution function is defined by the expression (7), whereas the probability of variable x to assume some value from the interval $[x_1, x_2]$ is calculated by the following expression:

$$P(x_1 < x_i \le x_2) = \int_{x_1}^{x_2} P(x_i) \cdot \mathrm{d}\,x = F(x_2) - F(x_1) \, . \tag{18}$$

Ako se označi sljedeće:

If the following is denoted:

$$x = q_{\mathrm{pr-Un-tr},n} \tag{19a}$$

ili

or

$$q_{\mathrm{pl\_un},n} \tag{19b}$$

u budućem razdoblju

in the future period

$$\bar{x} = q_{\mathrm{pr\_un-tr}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\mathrm{pr\_un-tr},n} \tag{20a}$$

ili

or

$$q_{\text{pl\_un}} = \frac{1}{N} \cdot \sum_{n=1}^{n=N} q_{\text{pl\_un},n} \; . \tag{20b}$$

Iterativnim putem moguće je naći vrijednost x za koju je vjerojatnost prema funkciji normalne razdiobe jednaka zadanoj vrijednosti, npr. $P(x) = 0{,}95$. Tada je vrijednost x jednaka predviđenoj neraspoloživosti razmatrane jedinice mreže radi trajnih prisilnih, odnosno planiranih zastoja s unutarnjim razlogom u budućoj razmatranoj godini.

Ukoliko se koristi Weibullova razdioba iz aritmetičke sredine uzorka i standardne devijacije izračunavaju se parametri razdiobe k i λ, te se pomoću inverzne Weibullove funkcije izračunava vrijednost x koja odgovara zadanoj vjerojatnosti, na pr. $P(x) = 0{,}95$. Tada je, kao i u prethodnom slučaju, vrijednost x jednaka predviđenoj neraspoloživosti razmatrane jedinice mreže radi trajnih prisilnih, odnosno planiranih zastoja s unutarnjim razlogom u budućoj razmatranoj godini.

Ukupna procijenjena neraspoloživost razmatranih jedinica jednaka je sumi procijenjenih neraspoloživosti radi prisilnih i planiranih zastoja zbog unutarnjih i vanjskih razloga.

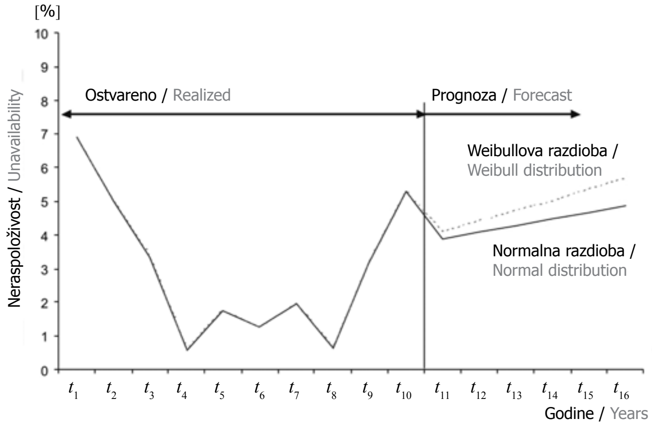
Nakon što se izračunaju iznosi neraspoloživosti radi prisilnih i planiranih zastoja s unutarnjim razlozima u prvoj budućoj godini ta se vrijednost pridruži osnovnom skupu (uzorku), opet se računa srednja vrijednost skupa i standardna devijacija iz čega se dobije procjena odgovarajuće neraspoloživosti za iduću godinu promatranja. Postupak se ponavlja sve dok nije obuhvaćeno čitavo buduće razdoblje promatranja. Primjer određivanja neraspoloživosti na opisani način prikazan je slikom 2.

then it is iteratively possible to find the value x for which the probability according to the normal distribution function equals the given value, e.g., $P(x) = 0{,}95$. Then the value x equals the anticipated unavailability of the observed network unit due to permanent or planned outages caused by internal reason in the future observed year.

If the Weibull distribution is used, the distribution parameters k and λ are obtained from the arithmetic mean of the sample and the standard deviation, and by means of the inverse Weibull function the value x is calculated which corresponds to the given value, e.g., $P(x) = 0{,}95$. Then, like in the previous case, the value x equals the anticipated unavailability of the observed network unit due to permanent forced or planned outages caused by internal reason in the future observed year.

The total assessed unavailability of studied units equals the sum of assessed unavailabilities due to forced and planned outages caused by internal and external reasons.

Once the amounts of unavailability due to forced and planned outages in the first future year have been calculated, that value is attached to the basic set (sample), the mean value of the basic set, the mean value of the set and the standard deviation are again calculated, from which an assessment of the corresponding unavailability for the next observation year is obtained. The procedure is repeated until the whole future observation period is covered. Figure 2 below gives an example of how unavailability is defined in the described way.



Slika 2 — Procjena buduće neraspoloživosti voda starijeg od 40 godina (Weibullova)
Figure 2 — Assessment of the future unavailability of a line older than 40 years (Weibull distribution)

4 PROBABILISTIČKE SIMULACIJE RADA EES-a

Korištena probabilistička simulacija (Monte-Carlo) zasniva se na stohastički modeliranim ulaznim podacima, velikom broju proračuna istosmjernih optimalnih tokova snaga i odgovarajućim optimizacijskim algoritmom za određivanje minimalne redukcije opterećenja elemenata mreže (vodova i transformatora).

U pripremi podataka za proračun prikupljaju se osnovni parametri jedinica prijenosne mreže, statistički se obrađuju podaci o njihovoj raspoloživosti iz statistike pogonskih događaja, vrši se procjena njihove neraspoloživosti u promatranom budućem razdoblju, zatim se određuje očekivana vrijednost vršnog opterećenja sustava i pripadna standardna devijacija, oblik godišnje krivulje trajanja opterećenja te struktura i parametri sadašnjih i budućih proizvodnih postrojenja.

Prijenosna mreža je definirana topologijom, odnosno popisom čvorišta i grana. Svaka grana je određena svojom uzdužnom impedancijom (r, x), neraspoloživošću (q) i maksimalno dozvoljenim strujom u normalnim (I_{max}) i izvanrednim uvjetima ($I_{\mathrm{max\ 20}}$).

Opterećenje i potrošnja po svakom čvorištu definirana je vršnim opterećenjem (snagom) i oblikom godišnje krivulje trajanja opterećenja koja se opisuje nizom koeficijenata. Zbog pojednostavljenja, a da se ne gubi fizikalni smisao, u daljnjim analizama pretpostavlja se da je oblik krivulje jednak za sva čvorišta u mreži. Očekivana vrijednost vršnog opterećenja rezultat je posebnih studija u kojima se promatra niz faktora koji utječu na potrošnju električne energije (bruto društveni proizvod, udio pojedinih gospodarskih sektora u stvaranju domaćeg proizvoda, utjecaj energetski intenzivne industrije, struktura i karakteristike trošila i drugo). Standardnom devijacijom uzimaju se u obzir nesigurnosti u predviđanju, utjecaj klimatskih faktora te nesigurnosti u priključku novih potrošača na mrežu. Godišnja krivulja trajanja opterećenja dijeli se na određeni broj dijelova konstantnog opterećenja (P) i vremena trajanja (t).

Svaka proizvodna termo jedinica modelira se maksimalnom snagom, raspoloživošću i prosječnim pogonskim troškovima. Hidroelektrane se dijele na dvije kategorije: protočne (njihova proizvodnja ovisna je o pretpostavljenoj hidrologiji), te akumulacijske (njihov angažman je promjenljiv, a ovisi o hidrologiji i načinu upravljanja akumulacijama).

Za prvu vrstu hidroelektrana zadaje se angažirana snaga koja tijekom proračuna ostaje konstantna,

4 PROBABILISTIC SIMULATIONS OF THE EPS OPERATION

The used probabilistic simulation (Monte-Carlo) is based on stochastically modeled input data, a great number of DC optimal power flow calculations and appropriate optimization algorithms for defining the minimum load reduction for the network elements (lines and transformers).

In preparing data for calculation, the basic parameters of the transmission network units are collected, data on their availability, taken from the statistics of operation events, are processed and their unavailability over the future observed period is assessed, which is followed by the definition of the expected peak load value of the system and the pertaining standard deviation, the shape of the annual load duration curve and the structure and parameters of the present and future generation facilities.

The transmission network is defined by the topology or the list of nodes and branches. Each branch is determined by its impedance (r, x), unavailability (q) and the maximum permitted electric current under normal (I_{max}) and emergency conditions ($I_{\mathrm{max\ 20}}$).

The load and demand per each node is defined by the peak load (power) and shape of the annual load duration curve described by a series of coefficients. For the sake of simplicity, but without losing the physical meaning of it, in the succeeding analyses it is assumed that the shape of the curve is equal for all nodes in the network. The expected peak load value is a result of special studies in which a series of factors are investigated, those influencing electricity consumption (gross social product, the share of special industrial sectors in the creation of domestic product, the impact of energy-intensive industry, the structure of energy users, etc.). With the standard deviation the uncertainties in forecasting, the impact of climatic factors and the uncertainties involved in the connection of new consumers to the network are taken into account. The annual load duration curve is divided into a certain number of parts of the constant load (P) and duration times (t).

Each thermal generation unit is modeled by maximum power, availability and average operating costs. Hydro power plants are divided into two categories: the run-of-river (output dependent on the assumed hydrology) and the storage power plants (with changeable engagement, depending on the local hydrology and storage management).

For the former type of hydro power plants engaged power is given which remains constant during the calculation, whereas given for the latter type dok se za drugi tip hidroelektrana zadaje maksimalna snaga i početno angažirana snaga koja se određuje na osnovi načina upravljanja akumulacijama i za koju su troškovi proizvodnje jednaki nuli. Radi dodatnog angažiranja akumulacijskih hidroelektrana s ciljem otklanjanja mogućih poremećaja u mreži pri pojedinim uklopnim stanjima definira se trošak dodatne hidro proizvodnje, koji u principu određuje način pražnjenja akumulacija.

Nakon određivanja stanja izgrađenosti proizvodnih postrojenja i troškova njihove proizvodnje (uzimaju se u obzir samo varijabilni troškovi) vrši se proračun istosmjernih optimalnih tokova snaga, odnosno rješava se optimizacijski problem:

are maximum power and initially engaged power which is defined on the basis of the way in which storages are run and for which the generation cost equals zero. For additional engagement of storage hydro plants with a view to eliminating possible network congestions in some operation conditions, the cost of additional hydro generation is defined, which in principle determines the method of storages management.

After ascertaining the constructed status of generation facilities and the costs of their power output (only the variable costs are taken into account), the DC optimal power flows are calculated. i.e., the optimization problem is being resolved:

$$\mathrm{Min}\left[\sum_i C_i(P_{\mathrm{G}i}) + \mu\sum_i H_i + \sum_i c_i P^{\mathrm{r}}_{\mathrm{D}i}\right], \tag{21}$$

$$P_{\mathrm{G}i\,\mathrm{min}} \le P_{\mathrm{G}i} \le P_{\mathrm{G}i\,\mathrm{max}} \quad , \tag{22}$$

$$0 \le H_i \le H_{i\,\mathrm{max}} \quad , \tag{23}$$

$$[\boldsymbol{B}]\cdot[\theta_i] - [\boldsymbol{P}_{\mathrm{G}i}] = [-\boldsymbol{P}_{\mathrm{D}i}] \quad , \tag{24}$$

$$\frac{1}{x_{ij}}\left(\theta_i - \theta_j\right) + s_{ij} = P_{ij}^{\max} \quad , \tag{25}$$

$$0 \le P^{\mathrm{r}}_{\mathrm{D}i} \le P_{\mathrm{D}i}\,, \tag{26}$$

gdje su:

$C_i(P_{\mathrm{G}i})$ – funkcija troškova proizvodnje generatora (ponuda generatora na tržištu)
$P_{\mathrm{G}i}$ – djelatna snaga generatora u čvoru i
$P_{\mathrm{D}i}$ – iznos tereta (opterećenja) u čvoru i
$P^{\mathrm{r}}_{\mathrm{D}i}$ – iznos reduciranog opterećenja u čvoru i
$P_{\mathrm{G}i\,\mathrm{mix}}$ – minimalna snaga generatora u čvoru i
$P_{\mathrm{G}i\,\mathrm{max}}$ – maksimalna snaga generatora u čvoru i
θ_i, θ_j – kutovi napona u čvorovima i i j
S_{ij} – dodatna varijabla u granicama 0-2$P_{ij}^{\max}$
$P_{ij}^{\max}$ – maksimalno dozvoljena djelatna snaga vodom između čvorova i, j
H_i – dodatna hidro proizvodnja u čvorištu i,
$H_{i\,\mathrm{max}}$ – maksimalna hidro proizvodnja u čvorištu i,
μ – jedinični troškovi dodatne hidro proizvodnje,

where:
$C_i(P_{\mathrm{G}i})$ – cost function of generator output (generator's bids on the market)
$P_{\mathrm{G}i}$ – generator's active power in node i
$P_{\mathrm{D}i}$ – amount of load in node i
$P^{\mathrm{r}}_{\mathrm{D}i}$ – amount of reduced load in node i
$P_{\mathrm{G}i\,\mathrm{mix}}$ – generator's minimum power in node i
$P_{\mathrm{G}i\,\mathrm{max}}$ – generator's maximum power in node i
θ_i, θ_j – voltage angles in nodes i and j
S_{ij} – additional variable within margins 0-2$P_{ij}^{\max}$
$P_{ij}^{\max}$ – maximum permissible active power by line between nodes i, j
H_i – additional hydro generation in node i,
$H_{i\,\mathrm{max}}$ – maximum hydro generation in node i,
μ – unit costs of additional hydro generation,
c_i – unit price of undelivered electricity in node i.

c_i – jedinični trošak neisporučene električne energije u čvoru i.

Topološka se nesigurnost (uklopno stanje generatora, vodova i transformatora) uzima u obzir korištenjem generatora pseudoslučajnih brojeva uniformne razdiobe koji se koriste za svaku jedinicu mreže (ukoliko je pseudoslučajni broj u intervalu $[0, p_{ij}]$ vod/transformator je u pogonu, ukoliko je pseudoslučajni broj u intervalu $(p_{ij}, 1]$ vod/transformator je izvan pogona, pri čemu je p_{ij} raspoloživost promatranog elementa ($p_{ij} = 1 - q_{ij}$); analogan je postupak za generatore). Prema tome, u svakoj simulaciji potrebno je generirati matricu susceptancija čvorova $\boldsymbol{B}$ sa slučajno određenim elementima ovisno o uklopnom stanju grana mreže.

Za svaki aproksimirani dio godišnje krivulje trajanja opterećenja izvodi se velik broj proračuna istosmjernih optimalnih tokova snaga, te se izračunavaju sljedeće prosječne vrijednosti:

- matematičko očekivanje godišnje neisporučene električne energije i
- troškovi neisporuke električne energije,
- ukupni troškovi proizvodnje elektrana u sustavu,
- ukupni operativni troškovi rada sustava,
- procjena očekivanog marginalnog smanjenja godišnje neisporučene električne energije pri povećanju kapaciteta svake grane u mreži za 1 MW.

Dobivene rezultate moguće je razvrstati prema uzroku nastanka:

- troškovi uzrokovani nedostatkom proizvodnih postrojenja, te
- troškovi uzrokovani ograničenjima u mreži.

Od interesa za ovaj rad samo su ona ograničenja uzrokovana slabostima mreže. Najvažnije veličine na temelju kojih se u kasnije opisanoj metodologiji određuje lista prioriteta za zamjene i rekonstrukcije ukupni su godišnji očekivani troškovi neisporučene električne energije uzrokovani slabostima mreže, te ukupni godišnji očekivani troškovi preraspodjele angažmana elektrana (u odnosu na minimalne troškove proizvodnje do kojih bi došlo ukoliko u mreži ne bi bilo ograničenja niti u jednom ispitanom pogonskom stanju) uzrokovani slabostima mreže.

Da bi se izbjeglo stohastičko modeliranje većeg broja ulaznih veličina moguće je primijeniti multiscenarijsku analizu kod koje se definira više mogućih i realnih scenarija s obzirom na neku ulaznu veličinu, a zatim se vrše probabilističke simulacije za svaki scenarij i izračunavaju prosječne izlazne vrijednosti varijabli od interesa. Ukoliko su pozna-

The topological uncertainty (the switching status of generators, lines and transformers) is taken into consideration by using generators of pseudo-random numbers of uniform distribution which are used for each network unit (if a pseudo-random number is in the interval $[0, p_{ij}]$ the line/transformer is in operation, if a pseudo-random number is in the interval $(p_{ij}, 1]$ line/transformer is out of operation, where p_{ij} is the availability of the observed element ($p_{ij} = 1 - q_{ij}$). The procedure is analogous for the generators). Therefore, in each simulation it is necessary to generate a susceptance matrix of nodes $\boldsymbol{B}$ with randomly defined elements in dependence on the switching status of network branches.

For each approximated part of the annual load duration curve a great number of DC optimal power flows calculations is performed, and the following average values are being computed:

- mathematically expected annual undelivered electricity,
- costs of undelivered electricity,
- total generation costs of power plants in the system,
- total operating costs of the system's operation,
- estimated expected marginal decrease in annually undelivered electricity with a capacity increase of every branch in the network by 1 MW.

The obtained results can be classified as follows:

- costs caused by the lack of generation facilities, and
- costs caused by network constraints.

Of interest for the present work are only the constraints caused by the network's weaknesses. The most important values based on which a priority list of replacements and reconstructions is compiled by means of the below described methodology are the total annual expected costs of undelivered electricity caused by the network's weaknesses and the total annual expected costs of power plants re-dispatch (relative to the minimum generation costs incurred if there were no constraints in the network in any tested operation state) caused by the network's weaknesses.

In order to avoid the stochastic modeling of a greater number of input values, it is possible to apply the multi-scenario analysis where a number of possible and real scenarios are defined relative to some input value and then probabilistic simulations are made for each scenario, and average output values of interest are computed. If the onset probabilities of particular scenarios (P_j, $j = 1, 2, ..., P_j$, M_s, where M_s is the total number te vjerojatnosti nastanka pojedinačnih scenarija ($P_j, j = 1, 2, ..., P_j, M_s$, gdje je M_s ukupni broj scenarija), tražena srednja vrijednost varijable x izračunava se kao suma umnožaka izračunatih vrijednosti x u svakom scenariju i vjerojatnosti nastanka tog scenarija:

of scenarios) are known, the sought mean value of variable x is calculated as a sum of the products of the calculated values x in each scenario and the onset probabilities of that scenario:

$$\bar{x} = \sum_{j=1}^{M_s} p_j x_j \ . \qquad (27)$$

5 KRITERIJI ZA REVITALIZACIJU VODOVA I TRANSFORMATORA

5.1 Metoda za ocjenu uloge i važnosti jedinica u prijenosnoj mreži

Uloga pojedinih vodova i transformatora u prijenosnoj mreži (elektroenergetskom sustavu) određuje se multi-scenarijskom analizom i probabilističkim simulacijama rada sustava. Unutar probabilističkih simulacija stohastički se modelira samo neraspoloživost pojedinih grana i generatora, odnosno promatra se samo topološka nesigurnost, budući da je ona od najvećeg interesa za određivanje liste prioriteta za revitalizaciju vodova i transformatora. Ostale vrste nesigurnosti (poput plana izgradnje novih elektrana, hidroloških okolnosti i dr.) modeliraju se kroz multi-scenarijsku analizu. Na osnovi izračuna operativnih troškova rada elektroenergetskog sustava tijekom cjelokupne godišnje krivulje trajanja opterećenja unutar promatranog kratkoročnog razdoblja određuje se utjecaj različitih razina neraspoloživosti promatranih vodova i transformatora na troškove rada sustava. Pri ocjeni uloge jedinica prijenosne mreže promatraju se svi definirani scenariji koji mogu biti ovisni o vremenskom presjeku, izgradnji novih elektrana, ponudama proizvođača, hidrološkim prilikama, bilanci sustava i drugim nesigurnostima unutar promatranog vremenskog razdoblja.

U svim analiziranim scenarijima pogona sustava za svaki se vod i transformator – kandidat za zamjene i rekonstrukcije, promatra pet razina njegove buduće neraspoloživosti, te se za svaku izračunava povećanje očekivanih godišnjih operativnih troškova rada EES-a radi slabosti u mreži:

— prosječna (vodovi i transformatori mlađi od 40 godina) ili procijenjena neraspoloživost vodova i transformatora (stariji od 40 godina), određene metodom opisanom u poglavlju 3,

5 CRITERIA FOR THE REVITALIZATION OF LINES AND TRANSFORMERS

5.1 The method of estimating the role and importance of units in the transmission network

The role of individual lines and transformers in a transmission network (EPS) is defined by the multi-scenario analysis and probabilistic simulations of the system's operation. Within the probabilistic simulations only the unavailability of individual branches and generators is stochastically modeled, i.e., only the topological uncertainty is observed, because it is of the greatest interest for compiling the priority list for the revitalization of lines and transformers. Other types of uncertainty (like a plan for the construction of new power plants, the factor of hydrological conditions, etc.) are modeled by using the multi-scenario analysis. Based on the calculated operating costs of the EPS during the entire annual load duration curve within an observed short-term period, the impact of different availability levels of the observed lines and transformers on the system's operating costs is determined. In assessing the role of the transmission network units, all the scenarios are observed that may depend on the time cross-section, the construction of new power plants, the generators' bids, the hydrological conditions, the system's balance and other uncertainties within the observed period of time.

In all the analyzed system operation scenarios, for each line and transformer – revitalization candidate, five levels of its future unavailability are observed and for each an increase in the expected annual operating costs of the EPS, due to weaknesses in the network, is calculated:

— the average (lines and transformers younger than 40 years) or estimated unavailability of lines and transformers (older than 40 years), defined by the method described in Section 3,

— prosječna neraspoloživost svih vodova i transformatora (pa i onih starijih od 40 godina), na temelju statistike pogonskih događaja,
— reducirana neraspoloživost vodova i transformatora starijih od 40 godina nakon izvođenja revitalizacije, pri čemu se neraspoloživost pojedinačnih kandidata određuje uz pretpostavku idealnog smanjenja na nulu trajnih prisilnih i planiranih zastoja s unutarnjim razlogom,
— trajna neraspoloživost voda ili transformatora (neraspoloživost 100 %),
— potpuna raspoloživost voda ili transformatora (neraspoloživost 0 %).

Uloga pojedinog voda ili transformatora ocjenjuje se na temelju razlika troškova rada sustava uzrokovanih slabostima u mreži za pojedine ispitivane razine raspoloživosti promatranih vodova i transformatora. Za ocjenu uloge pojedinih vodova i transformatora uvode se sljedeće oznake:

$MC_{i,\mathrm{k}}(j)$: marginalna dobit od povećanja kapaciteta voda ili transformatora k (smanjenje operativnih troškova rada EES-a pri povećanju prijenosne moći voda ili prividne snage transformatora k za 1 MW) u i-toj godini, za j-ti analizirani scenarij, uz procijenjenu neraspoloživost vodova i transformatora u mreži.

$OC_i(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij ovisan o modeliranim nesigurnostima, uz procijenjenu neraspoloživost vodova i transformatora u mreži.

$OC_{i,\mathrm{k}}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz neraspoloživost voda ili transformatora k jednaku prosječnoj vrijednosti u proteklom razdoblju obuhvaćenim statistikom pogonskih događaja.

$OC'_{i,\mathrm{k}}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz neraspoloživost voda ili transformatora k jednaku prosječnoj vrijednosti u proteklom razdoblju obuhvaćenom statistikom pogonskih događaja umanjenoj za trajne prisilne i planirane zastoje s unutarnjim razlogom.

$OC_{i,\mathrm{kl}}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz potpunu neraspoloživost voda ili transformatora k.

— the average unavailability of all lines and transformers (including those older than 40 years), based on the statistics of operation events,
— reduced unavailability of lines and transformers older than 40 years after performed revitalization, where the unavailability of particular candidates is defined under the assumption of ideal reduction to zero permanent forced and planned outages caused by internal reason,
— permanent unavailability of a line or transformer (unavailability 100 %),
— full availability of a line or transformer (unavailability 0 %).

The role of a line or transformer is assessed on the basis of differences in the system's operating costs caused by weaknesses in the network for particular tested availability levels of the observed lines and transformers. For an assessment of the role of individual lines and transformers the following variables are introduced:

$MC_{i,\mathrm{k}}(j)$: marginal gain from the increased capacity of a line or transformer k (decrease in the EPS's operating costs at an increase in the transmission capability of the line or the apparent power of transformer k by 1 MW) in the i-th year, for the j-th analyzed scenario, given the estimated unavailability of lines and transformers in the network.

$OC_i(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario dependent on modeled uncertainties, given the estimated unavailability of lines and transformers in the network.

$OC_{i,\mathrm{k}}(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given the unavailability of the line or transformer k equal to the average value in the past period covered by the statistics of operation events.

$OC'_{i,\mathrm{k}}(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given the unavailability of the line or transformer k equal to the average value in the past period covered by the statistics of operation events, reduced by the permanent forced and planned outages for an internal reason.

$OC_{i,\mathrm{kl}}(j)$: the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given total unavailability of the line or transformer k.

$OC_{i,\mathrm{k}0}(j)$: godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži u i-toj godini za j-ti analizirani scenarij uz potpunu raspoloživost voda ili transformatora k.

5.2 Kriteriji ovisni o stvarnom stanju jedinice

Stvarno stanje jedinica prijenosne mreže moguće je ocijeniti analizom i obradom različitih podataka vezanih za starost jedinice, pogonske uvjete kojima je bila izložena, povijest održavanja, vizualne inspekcije, dijagnostičke rezultate i dr. Cilj ocjenjivanja stvarnog stanja jedinica je prvenstveno određivanje kandidata za revitalizaciju, te određivanje visine ulaganja financijskih sredstava i aktivnosti koje je potrebno izvršiti nad promatranom jedinicom.

5.2.1 Starost jedinice

Starenje jedinica prijenosne mreže kontinuirani je proces tijekom kojega se narušava funkcionalnost istih. Za sve grupe istovrsnih jedinica prijenosne mreže (u ovom se radu promatra četiri grupe: 1) nadzemni vodovi, 2) kabelski vodovi, 3) kombinirani nadzemno-kabelski vodovi, 4) transformatori) definira se očekivana životna dob tih jedinica na temelju statističke analize podataka iz prošlosti (koji su ograničeni zbog relativno kratkog razdoblja funkcioniranja modernih izmjeničnih sustava električne energije).

Starost jedinice, u odnosu na očekivanu životnu dob grupe istovrsnih jedinica, određeni je pokazatelj njenog mogućeg stanja. Sve jedinice starije od očekivane životne dobi grupe istovrsnih jedinica potencijalni su kandidati za revitalizaciju, iako u konačnici možda neće biti nužno izvoditi bilo kakve aktivnosti na revitalizaciji ukoliko su ostali pokazatelji stanja promatrane jedinice povoljni. Prema tome, kandidat za revitalizaciju svaka je jedinica prijenosne mreže za koju je zadovoljeno:

$OC_{i,\mathrm{k}0}(j)$: : the system's annual operating costs resulting from weaknesses in the network in the i-th year for the j-th analyzed scenario given full availability of the line or transformer k.

5.2 Criteria dependent on the real condition of a unit

The real condition of transmission network units can be assessed by analyzing and processing various data relating to the age of a unit, the operation conditions to which it was exposed, the history of maintenance, visual inspections, diagnostic results, etc. The purpose of assessing the real condition of the units is first of all to get a list of revitalization candidates and to appraise the amount of required finances, as well as activities to be carried out on the observed unit.

5.2.1 The age of a unit

The aging of transmission network units is an ongoing process in the course of which their functionality is being impaired. For all the groups comprising transmission network units of the same type (in the present work four groups are examined: 1) overhead lines, 2) cables, 3) combined overhead-cable lines, 4) transformers) life expectancy of these units is defined based on a statistical analysis of these past data (which are limited due to a relatively short operation period of modern AC power systems).

The age of a unit in relation to the life expectancy of a group of units of the same type is an indicator of its likely condition. All the units older than the life expectancy of the group of units of the same type are potential revitalization candidates, although eventually it may not be necessary to undertake any revitalization if the other indicators of the condition of the observed unit are favorable. Therefore, a revitalization candidate is any of the transmission network units for which the following requirement is met:

$$T_\mathrm{k} \geq T \ , \qquad (28)$$

gdje je T_k starost promatrane jedinice k, a T očekivana životna dob grupe istovrsnih jedinica prijenosne mreže (radi pojednostavljenja može se uzeti $T = 40$ godina za promatrane grupe jedinica, tj. za vodove i transformatore).

5.2.2 Neraspoloživost jedinice

Za starije jedinice prijenosne mreže očekuje se porast njihove neraspoloživosti. Kao kandidate za revitalizaciju potrebno je izdvojiti sve jedinice čija

where T_k is the age of the observed unit k, and T is the life expectancy of the group of transmission network units of the same type (for the sake of simplicity we can take $T = 40$ years for the observed groups of units, i.e., lines and transformers).

5.2.2 Unavailability of units

For older transmission network units an increase in their unavailability is expected. As revitalization candidates all those units should be singled out je prosječna neraspoloživost u proteklom petogodišnjem razdoblju obuhvaćenom statistikom pogonskih događaja veća od prosječne neraspoloživosti u istom razdoblju cjelokupne grupe istovrsnih jedinica, odnosno one jedinice kod kojih je:

the average unavailability of which over the past five-year period covered by the operation statistics exceeds the average unavailability in the same period of the whole group of units of the same type, or those units with which:

$$\begin{array}{l} \bar{q}_{\mathrm{k}} \geq \bar{q}_{\mathrm{NV}} \\ \bar{q}_{\mathrm{k}} \geq \bar{q}_{\mathrm{K}} \\ \bar{q}_{\mathrm{k}} \geq \bar{q}_{\mathrm{NK}} \\ \bar{q}_{\mathrm{k}} \geq \bar{q}_{\mathrm{T}} \end{array} , \qquad (29)$$

gdje su:

$\bar{q}_{\mathrm{k}}$ – prosječna neraspoloživost promatrane jedinice k u zadnjem petogodišnjem razdoblju,
$\bar{q}_{\mathrm{NV}}$ – prosječna neraspoloživost svih nadzemnih vodova u promatranoj mreži u zadnjem petogodišnjem razdoblju,
$\bar{q}_{\mathrm{K}}$ – prosječna neraspoloživost svih kabelskih vodova u promatranoj mreži u zadnjem petogodišnjem razdoblju,
$\bar{q}_{\mathrm{NK}}$ – prosječna neraspoloživost svih kombiniranih nadzemno-kabelskih vodova u promatranoj mreži u zadnjem petogodišnjem razdoblju,
$\bar{q}_{\mathrm{T}}$ – prosječna neraspoloživost svih transformatora u promatranoj mreži u zadnjem petogodišnjem razdoblju.

5.2.3 Rezultati pregleda i dijagnostike jedinice

Stanje promatrane jedinice prijenosne mreže moguće je ocijeniti vizualnim pregledom ili podvrgavanjem određenim dijagnostičkim postupcima. Kompanija u čijem su vlasništvu jedinice prijenosne mreže, odnosno posebni odjeli zaduženi za upravljanje imovinom, redovito provodi vizualnu inspekciju opreme, a po potrebi podvrgavaju određenu opremu i dijagnostičkim ispitivanjima. Kao kandidati za revitalizaciju uvrštavaju se sve one jedinice čiji vizualni pregledi ili rezultati dijagnostike ukazuju na njihovu smanjenu funkcionalnost i općenito ugroženost.

5.2.4 Troškovi održavanja jedinice

Svaka jedinica tijekom svog životnog vijeka redovito se održava kako bi se očuvala njena funkcionalnost. U održavanje se ulažu određena financijska sredstva koja su na razini pojedinih vremenskih razdoblja približno konstantna. Starije jedinice mreže generalno zahtijevaju veća financijska sredstva potrebna za održavanje. Broj unutarnjih kvarova sve je veći pa raste i potreba za aktivnostima na njihovom otklanjanju. Istodobno raste i potreba preventivnog održavanja, odnosno planiranih zastoja, kako bi se otklanjali pojedini nedostaci i omogućilo normalno funkcioniranje jedinice. Kao kandidati za revitalizaciju izdvojene

where:

$\bar{q}_{\mathrm{k}}$ – average unavailability of the observed unit k in the last five-year period,
$\bar{q}_{\mathrm{NV}}$ – average unavailability of all overhead lines in the observed network in the last five-year period,
$\bar{q}_{\mathrm{K}}$ – average unavailability of all cables in the observed network in the last five-year period,
$\bar{q}_{\mathrm{NK}}$ – average unavailability of all combined overhead-cable lines in the observed network in the last five-year period,
$\bar{q}_{\mathrm{T}}$ – average unavailability of all transformers in the observed network in the last five-year period.

5.2.3 Inspection and diagnostic results

The state of an observed transmission network unit can be assessed through visual inspection or by subjecting it to certain diagnostic procedures. The company which owns the transmission network units, i.e., its specialized departments in charge of assets management, conducts regular visual inspections of the equipment and, as required, subject certain equipment to diagnostic tests. As revitalization candidates qualify all those units the visual inspections of which or diagnostic results suggest diminished functionality or, generally, vulnerability.

5.2.4 Maintenance costs

Each unit is regularly maintained throughout its lifetime in order to preserve its functionality. Certain funds are spent on maintenance which are approximately constant at the level of particular periods of time. Older network units generally require more maintenance funds. Internal failures are steadily rising in number, and so is a need for activities aimed to correct them. At the same time, a need is rising for preventive maintenance, and thereby for planned outages, so as to eliminate certain irregularities and enable the unit concerned to function normally. Singled out as revitalization su one jedinice čiji su troškovi održavanja, promatrano u određenom vremenskom razdoblju (na primjer u godini dana), znatno veći od troškova preventivnog održavanja, odnosno troškova održavanja istovrsnih novijih jedinica mreže. Prema tome, kandidat za zamjene i rekonstrukcije svaka je jedinica prijenosne mreže za koju je zadovoljeno:

candidates are those units the maintenance costs of which, viewed over a certain period of time (e.g., a year's time), by far exceed the preventive maintenance costs, or the maintenance costs of new network units of the same type. Therefore, a candidate for revitalization is any of the transmission network units for which the following requirement is met:

$$C_{\mathrm{m}}(\mathrm{k}) \gg C_{\mathrm{pm}}(\mathrm{k})\,, \tag{30}$$

gdje su:

$C_{\mathrm{m}}(\mathrm{k})$ – aktualni godišnji troškovi održavanja promatrane jedinice k, a
$C_{\mathrm{pm}}(\mathrm{k})$ – godišnji troškovi preventivnog održavanja novije jedinice istovjetne jedinici k.

5.2.5 Tehničko stanje jedinica i ostali pokazatelji stanja

Pod kriterijima za ocjenu tehničkog stanja jedinica prijenosne mreže svrstavaju se: tehnička neispravnost jedinice ili komponente, tehnička greška jedinice ili komponente mreže takva da je ekonomski neisplativo tu grešku otkloniti, nezadovoljavajuće karakteristike jedinice ili komponente mreže s obzirom na očekivane pogonske uvjete u planskom razdoblju (opterećenja, kratki spoj), nezadovoljavanje postojećih i budućih tehničkih propisa koje jedinica mreže mora zadovoljavati. Pod tehnički neispravnom jedinicom ili komponentom mreže podrazumijeva se ona jedinica ili komponenta mreže koja je trajno u stanju zastoja radi kvara, te ona jedinica ili komponenta mreže koja je u pogonu, ali predstavlja opasnost ili rizik za ljude ili imovinu i ispravno funkcioniranje ostalih jedinica i komponenti mreže. Pod tehničkom greškom jedinice ili komponente prijenosne mreže podrazumijeva se posljedica događaja koji promatranu jedinicu postavlja u stanje privremene ili trajne neispravnosti. Kao kandidate za revitalizaciju izdvajaju se sve jedinice koje ne zadovoljavaju neki od nabrojenih tehničkih kriterija. Osim navedenog, na stanje jedinica prijenosne mreže i potrebe revitalizacije značajan utjecaj mogu imati i određene okolnosti izvan promatranih jedinica, kao što su nedostatak osoblja obučenog za održavanje pojedinih tipova komponenata mreže, nedostatak rezervnih dijelova nužnih za normalan pogon jedinice ili komponente mreže, nezadovoljenje različitih propisa vezanih za zaštitu okoliša, nezadovoljenje različitih zahtjeva regulatorne agencije, te ugroženost osoblja zaduženog za održavanje i okolne opreme.

where:

$C_{\mathrm{m}}(\mathrm{k})$ – annual actual maintenance costs of the observed unit k, and
$C_{\mathrm{pm}}(\mathrm{k})$ – annual preventive maintenance costs of a new unit identical to unit k.

5.2.5 Technical condition of units and other status indices

Classified under the criteria for an assessment of the technical condition of the transmission network units are: the technical faultiness of a unit or component, the technical error of a network unit or component, such as making the rectification of the error commercially unfeasible, unsatisfactory characteristics of a network unit or component in respect of the expected operation conditions in the planning period (loads, short-circuits), non-compliance with the existing and future technical regulations that a network unit must comply with. By a technically faulty network unit or component is meant one which is permanently in a state of outage caused by a failure, as well as one which is in operation but poses a risk to persons and property and to the proper functioning of other network units and components. By a technical error of a transmission network unit or component is meant the consequence of an event that places the observed unit in a state of temporary or permanent faultiness. Singled out as revitalization candidates are those units which do not meet one of the specified technical criteria. Apart from the aforementioned, the state of the transmission network units and the need for revitalization can also be significantly influenced by some circumstances outside the observed units, such as the shortage of staff trained for the maintenance of specific types of the network components, the shortage of spare parts needed for normal operation of a network unit or component, non-compliance with various regulations relating to environmental protection, non-compliance with various regulations passed by the regulatory agency, risk exposure of personnel doing maintenance on nearby equipment.

5.3 Kriteriji ovisni o ulozi i važnosti jedinice unutar EES-a

5.3.1 Kriterij povećanja očekivanih operativnih troškova rada elektroenergetskog sustava (starosni kriterij)

Unutar razmatranog kriterija izračunavaju se očekivani godišnji operativni troškovi rada elektroenergetskog sustava pri procijenjenoj neraspoloživosti voda ili transformatora k kandidata za revitalizaciju ($OC_i(j)$), za sve analizirane vremenske presjeke i i scenarije pogona j, te očekivani godišnji operativni troškovi rada elektroenergetskog sustava pri prosječnoj neraspoloživosti promatranog voda ili transformatora k u razdoblju obuhvaćenom statistikom pogonskih događaja ($OC_{i,k}(j)$). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti te razlike:

5.3 Criteria dependent on the role and importance of a unit within the EPS

5.3.1 Criterion of an increase in the EPS's expected operating costs (age criterion)

Calculated within the reviewed criterion are the EPS's expected annual operating costs at the estimated unavailability of a line or a transformer k, the revitalization candidates ($OC_i(j)$), for all analyzed time cross-sections i and operation scenarios j, and the EPS's expected annual operating costs at the average unavailability of an observed line or transformer k in the period covered by the statistics of operation events ($OC_{i,k}(j)$). For all the observed time cross-sections i, and operation scenarios j the average values of that difference are calculated:

$$\overline{OC_i(j) - OC_{i,\mathrm{k}}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_i(j) - OC_{i,\mathrm{k}}(j)\right] p_j}{N_i} \tag{31}$$

gdje je:

P_j – vjerojatnost nastanka scenarija j unutar promatrane godine i,
N_i – ukupni broj godina unutar promatranog vremenskog razdoblja,
N_j – ukupni broj scenarija.

where:

P_j – probability of the occurrence of scenario j within the observed year i,
N_i – total number of years within the observed period of time,
N_j – total number of scenarios.

Parcijalna lista prioriteta za revitalizaciju s obzirom na promatrani kriterij određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava pri procijenjenoj neraspoloživosti voda ili transformatora k, kandidata za revitalizaciju, te očekivanih godišnjih operativnih troškova rada elektroenergetskog sustava pri prosječnoj neraspoloživosti promatranog voda ili transformatora k u razdoblju obuhvaćenom statistikom pogonskih događaja:

A partial priority list for revitalization in respect of the observed criterion is compiled on the basis of a maximum average difference between the system's expected annual operating costs at the estimated unavailability of a line or transformer k, the revitalization candidates, and the EPS's expected annual operating costs at the average unavailability of the observed line or transformer k in the period covered by the statistics of operation events:

$$\mathrm{Max}\left\{\overline{OC_i(j) - OC_{i,\mathrm{k}}(j)}\right\}. \tag{32}$$

Prema tome, za sve analizirane vremenske presjeke i, te scenarije pogona j, traži se maksimalna prosječna razlika između povećanja operativnih troškova rada sustava uzrokovanih slabostima u mreži pri procijenjenoj neraspoloživosti vodova ili transformatora i povećanja operativnih troškova rada sustava pri raspoloživosti pojedinačnih vodova ili transformatora određenoj na temelju prosjeka u razdoblju obuhvaćenom statistikom pogonskih

Therefore, for all the analyzed time cross-sections i and operation scenarios j a maximum average difference is sought between the increase in the system's operating costs caused by weaknesses in the network at the estimated unavailability of lines or transformers and the increase in the system's operating costs at the availability of individual lines or transformers defined on the basis of the average in the period covered by the događaja. Vod ili transformator s najvećom razlikom između te dvije veličine najvažniji je kandidat za revitalizaciju u promatranoj kategoriji.

Za razmatranje ovog kriterija osnovna je pretpostavka da će se za vodove i transformatore starije od 40 godina neraspoloživost povećavati u svakoj promatranoj godini u kratkoročnom razdoblju, što će rezultirati povećanjem troškova rada EES-a za pojedine vodove i transformatore. Razlika između tako određenih troškova rada sustava i troškova rada sustava ukoliko bi se neraspoloživosti pojedinačnih vodova ili transformatora održavale na postignutom prosjeku u proteklom razdoblju, ujedno prikazuje i djelomičnu procjenu ekonomske opravdanosti ulaganja u održavanje ili revitalizaciju pojedinih vodova i transformatora,kojim bi se izbjeglo povećanje njihove neraspoloživosti.

5.3.2 Kriterij smanjenja očekivanih operativnih troškova rada EES-a nakon revitalizacije (ekonomski kriterij)

Unutar razmatranog kriterija promatra se najveća prosječna razlika očekivanih godišnjih operativnih troškova rada elektroenergetskog sustava pri procijenjenoj neraspoloživosti pojedinačnih vodova i transformatora k, kandidata za revitalizaciju ($OC_{i,\,\mathrm{kl}}(j)$), te neraspoloživosti tih vodova jednakoj prosječnoj vrijednosti u proteklom razdoblju obuhvaćenom statistikom pogonskih događaja umanjenoj za trajne prisilne i planirane zastoje s unutarnjim razlogom ($OC_i(j)$). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti te razlike:

statistics of operation events. The line or transformer with the greatest difference between these two values is the most important revitalization candidate in the observed category.

In examining this criterion the basic assumption is that for the lines and transformers older than 40 years unavailability will rise in every observed year in a short-term period, which will result in higher operating costs of the EPS for particular lines and transformers. The difference between the thus determined operating costs of the system and the operating costs of the system if the unavailabilities of individual lines or transformers were kept at the average rate attained in the previous period also partially illustrates the economic justification of investment in the maintenance or revitalization of some lines and transformers with a view to avoiding an increase in their unavailability.

5.3.2 Criterion of reduction in the expected operating costs of the EPS after revitalization (economic criterion)

Within the examined criterion the greatest average difference is observed between the expected annual operating costs of the EPS at the estimated unavailability of particular lines and transformers k, the revitalization candidates ($OC_{i,\,\mathrm{kl}}(j)$), and the unavailability of these lines equal to the average value in the previous period covered by the statistics of operation events reduced by permanent forced and planned outages occurred for an internal reason ($OC_i(j)$). For all the observed time cross-sections i and operation scenarios j the average values of that difference are calculated:

$$\overline{OC_i(j) - OC'_{i,\mathrm{k}}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_i(j) - OC'_{i,\mathrm{k}}(j)\right]\cdot p_j}{N_i} \quad . \tag{33}$$

Parcijalna lista prioriteta s obzirom na promatrani kriterij određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava za promatrane razine neraspoloživosti kandidata za revitalizaciju k:

The partial priority list against the observed criterion is defined on the basis of a maximum average difference between the expected annual operating costs of the system for the observed unavailability levels of the revitalization candidates k:

$$\mathrm{Max}\left\{\overline{OC_i(j) - OC'_{i,\mathrm{k}}(j)}\right\} \quad . \tag{34}$$

Pretpostavka je da će se za vodove i transformatore starije od 40 godina neraspoloživost povećavati u svakoj promatranoj godini u kratkoročnom razdoblju, što će rezultirati u povećanju troškova rada EES-a. Razlika između tako određenih troš-

It is assumed that for lines and transformers older than 40 years unavailability will rise in every observed year in a short-term period, which will result in increased operating costs of the EPS. The difference between the thus determined operating kova rada sustava i troškova rada sustava ukoliko bi svaki pojedinačni vod i transformator imao manju neraspoloživost kao rezultat određenih aktivnosti na revitalizaciji, prikazuje procjenu ekonomske opravdanosti ulaganja u revitalizaciju pojedinih vodova i transformatora kojim bi se povećala njihova raspoloživost, u idealnom slučaju do vrijednosti određene samo pod utjecajem zastoja s vanjskim razlozima, te privremenih i prolaznih prisilnih zastoja s unutarnjim razlogom. U stvarnim okolnostima neće se moći postići nulta neraspoloživost radi trajnih prisilnih i planiranih zastoja s unutarnjim razlogom niti jednog voda i transformatora na kojem su provedene aktivnosti na revitalizaciji, pa promatramo idealnu ekonomsku dobit od revitalizacije.

5.3.3 Kriterij opasnosti od trajnog otkaza

Za razmatrani kriterij promatra se najveća razlika između prosječnih očekivanih godišnjih operativnih troškova rada EES-a pri trajnoj neraspoloživosti ($OC_{i,\,\mathrm{kl}}(j)$) i procijenjenoj neraspoloživosti pojedinačnih vodova i transformatora k ($OC_i(j)$), kandidata za revitalizaciju. Izračunavaju se očekivani godišnji operativni troškovi rada sustava uzrokovani slabostima u mreži pri trajno isključenoj pojedinačnoj grani (vodu ili transformatoru) tijekom čitavog promatranog razdoblja za sve analizirane scenarije pogona, te se nadalje izračunava razlika između tako određenih troškova i troškova u baznom stanju definiranim procijenjenom neraspoloživosti vodova i transformatora. Na temelju razmatranog kriterija, a ovisno o stvarnom stanju vodova, može se definirati operativna lista prioriteta za revitalizaciju vodova s ciljem izbjegavanja porasta troškova rada sustava kod trajne obustave pogona nekog voda (npr. radi lošeg stanja stupova, pucanja vodiča, ugrožavanja sigurnosnih propisa i sl.) ili transformatora (npr. radi curenja ulja, korozije kotla i dr.). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti razlike očekivanih operativnih troškova rada sustava pri trajnoj neraspoloživosti i procijenjenoj neraspoloživosti kandidata:

costs of the system and the operating costs of the system if each particular line and transformer were less unavailable as a result of certain revitalization activities illustrates the assessed economic justification of investment in the revitalization of certain lines and transformers with a view to increasing their availability, in an ideal case up to the value defined only under the influence of an outages occurred for external reasons, and temporary and transient forced outages for an internal reason. In real circumstances the zero unavailability, due to permanent forced and planned outages caused by internal reason, will not be attainable with any line and transformer on which revitalization has been carried out, so we are focused on an ideal economic gain from revitalization.

5.3.3 Criterion of a risk of permanent failure

Examined for the criterion in question is the greatest difference between the average expected annual operating costs of the EPS at a permanent unavailability ($OC_{i,\,\mathrm{kl}}(j)$) and the estimated unavailability of particular lines and transformers k ($OC_i(j)$), the revitalization candidates. The expected annual operating costs of the system caused by weaknesses in the network at a permanently switched-off particular branch (line or transformer) throughout the observed period for all the analyzed operation scenarios are calculated. Further calculated is the difference between the thus defined costs and the base state costs defined by the estimated unavailability of lines and transformers. Based on the examined criterion and depending on the real condition of the lines, it is possible to define the operating priority list for the revitalization of the lines with a view to avoiding an increase in the operating costs of the system in the event of permanently discontinued operation of a line (e.g., due to poor condition of the towers, wire breakage, infringement of safety regulations and the like) or a transformer (e.g., due to oil leakage, boiler corrosion, etc.). For all the observed time cross-sections i and operation scenarios j the average differences are calculated between the expected operating costs of the system at permanent unavailability and the estimated unavailability of candidates:

$$\overline{OC_{i,\mathrm{k}1}(j)-OC_i(j)}=\frac{\displaystyle\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_{i,\mathrm{k}1}(j)-OC_i(j)\right]\cdot p_j}{N_i} \qquad (35)$$

Parcijalna lista prioriteta prema razmatranom kriteriju određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava za promatrane razine neraspoloživosti kandidata k:

The partial priority list against the observed criterion is defined on the basis of a maximum average difference between the expected annual operating costs of the system for the observed unavailability levels of the candidates k:

$$\text{Max}\ \left\{\overline{OC_{i,\mathrm{k}1}(j)-OC_{i}(j)}\right\} \tag{36}$$

Za sve analizirane vremenske presjeke i, i scenarije pogona j, traži se maksimalna razlika između povećanja operativnih troškova rada sustava pri trajnoj neraspoloživosti pojedinog voda ili transformatora i povećanja operativnih troškova rada sustava pri procijenjenoj neraspoloživosti vodova i transformatora. Vod ili transformator s najvećom razlikom između te dvije veličine najvažniji je kandidat za revitalizaciju u promatranoj kategoriji.

5.3.4 Kriterij važnosti jedinice u EES-u

Unutar razmatranog kriterija izračunavaju se očekivani godišnji operativni troškovi rada EES-a pri trajnoj neraspoloživosti voda ili transformatora k, kandidata za revitalizaciju ($OC_{i,\,\mathrm{kl}}\,(j)$), za sve analizirane vremenske presjeke i i scenarije pogona j, te očekivani godišnji operativni troškovi rada EES-a pri punoj raspoloživosti promatranog voda ili transformatora k ($OC_{i,\,\mathrm{k}0}\,(j)$). Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne vrijednosti te razlike:

For all the analyzed time cross-sections i and operation scenarios j a maximum average difference is sought between the increase in the system's operating costs at permanent unavailability of a line or a transformer and the increase in the system's operating costs at the availability of the lines and transformers. The line or transformer with the greatest difference between these two values is the most important revitalization candidate in the observed category.

5.3.4 Criterion of the importance of a unit in the EPS

Calculated within the criterion in question are the expected annual operating costs of the EPS at permanent unavailability of a line or transformer k, the revitalization candidates ($OC_{i,\,\mathrm{kl}}\,(j)$), for all the analyzed time cross-sections i and operation scenarios j and the expected annual operating costs of the EPS at full availability of the observed line or transformer k ($OC_{i,\,\mathrm{k}0}\,(j)$). For all the reviewed time cross-sections i and operation scenarios j the average values of that difference are calculated:

$$\overline{OC_{i,\mathrm{k}1}(j)-OC_{i,\mathrm{k}0}(j)}=\frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[OC_{i,\mathrm{k}1}(j)-OC_{i,\mathrm{k}0}(j)\right]p_j}{N_i} \tag{37}$$

Parcijalna lista prioriteta s obzirom na promatrani kriterij određuje se na temelju maksimalne prosječne razlike između očekivanih godišnjih operativnih troškova rada sustava pri trajnoj neraspoloživosti voda ili transformatora k, kandidata za revitalizaciju, te očekivanih godišnjih operativnih troškova rada EES-a pri punoj raspoloživosti promatranog voda ili transformatora k:

The partial priority list against the observed criterion is defined on the basis of a maximum average difference between the expected annual operating costs of the system at permanent unavailability of a line or transformer k, the revitalization candidates, and the expected annual operating costs of the EPS at full availability of the observed line or transformer k:

$$\text{Max}\ \left\{\overline{OC_{i,\mathrm{k}1}(j)-OC_{i,\mathrm{k}0}(j)}\right\}. \tag{38}$$

Vod ili transformator s najvećom razlikom između te dvije veličine najvažniji je kandidat za revitalizaciju u promatranoj kategoriji. Razlika između prosječnih očekivanih godišnjih operativnih troškova rada sustava pri trajnoj neraspoloživosti i punoj raspoloživosti kandidata ukazuje na važnost tog kandidata u EES-u. Kandidat s maksimalnom razlikom promatranih troškova najznačajnija je grana unutar sustava.

The line or transformer with the greatest difference between these two values is the most important revitalization candidate in the observed category. The difference between the average expected annual operating costs of the system at permanent unavailability and full availability of a candidate points to the importance of that candidate in the EPS. The candidate with a maximum difference of observed costs is the most important branch within the system.

5.3.5 Kriterij maksimalne marginalne dobiti

Unutar razmatranog kriterija promatra se najveća marginalna dobit neke grane (voda ili transformatora) za sve analizirane vremenske presjeke i i scenarije pogona j. Na taj način definiramo listu prioriteta onih vodova i transformatora kojima kroz revitalizaciju eventualno treba povećati prijenosnu moć ili prividnu snagu, ugradnjom vodiča većeg presjeka, vodiča s većim dozvoljenim termičkim opterećenjem ili zamjenom transformatora jedinicom veće prividne snage. Prije donošenja odluke o takvoj zamjeni vodiča ili transformatora potrebno je detaljno sagledati ekonomsku dobit koja iz te zamjene slijedi.

Za sve promatrane vremenske presjeke i, i scenarije pogona j, izračunavaju se prosječne marginalne dobiti grana:

5.3.5 Criterion of maximum marginal gain

Reviewed within the criterion in question is the highest marginal gain of a branch (line or transformer) for all the analyzed time cross-sections i and operation scenarios j. In this way we define the priority list of those lines and transformers transmission capacity or rated power of which may have to be enhanced through revitalization by installing a larger- cross-section conductor, a conductor with a higher permissible thermal load, or by replacing the transformer with a unit of higher apparent power. Before deciding on such a replacement of the conductor or transformer it is necessary to consider in detail the economic gains that the replacement may bring.

For all the reviewed time cross-sections i and operation scenarios j the average marginal gains of the branches are calculated:

$$\overline{MC_{i,\mathrm{k}}(j)} = \frac{\sum_{i=1}^{N_i}\sum_{j=1}^{N_j}\left[MC_{i,\mathrm{k}}(j)\right]\cdot p_j}{N_i} \quad , \qquad (39)$$

gdje su:

$MC_{i,\mathrm{k}}(j)$ – marginalne dobiti grane k u godini i i scenariju pogona j,
P_j – vjerojatnost nastanka scenarija j unutar promatrane godine i, a
N_i – broj godina unutar promatranog vremenskog razdoblja.

Lista prioriteta prema razmatranom kriteriju određuje se na temelju maksimalne prosječne marginalne dobiti:

where:

$MC_{i,\mathrm{k}}(j)$ – marginal gains of branch k in year i and operation scenario j,
P_j – probability of the occurrence of scenario j within the observed year i, and
N_i – number of years within the observed period of time.

The priority list against the criterion in question is defined on the basis of maximum average marginal gain:

$$\mathrm{Max}\left\{\overline{MC_{i,\mathrm{k}}(j)}\right\} . \qquad (40)$$

Za sve analizirane vremenske presjeke i scenarije pogona traži se maksimalna marginalna dobit pojedinog voda ili transformatora. Vod ili transformator s najvećom marginalnom dobiti najvažniji je kandidat za revitalizaciju u promatranoj kategoriji.

For all the analyzed time cross-sections and operation scenarios the maximum marginal gain of a line or transformer is sought. The line or transformer with the highest marginal gain is the most important revitalization candidate in the observed category.

6 METODOLOGIJA IZRADE LISTE PRIORITETA ZA REVITALIZACIJU

Budući da su u prethodnom poglavlju definirani pojedinačni kriteriji za revitalizaciju potrebno je

6 METHODOLOGY OF COMPILING A PRIORITY LIST FOR REVITALIZATION

In the preceding section the particular revitalization criteria are defined, so it is necessary to comujediniti sve kriterije te izraditi zajedničku listu prioriteta. Radi toga su definirane dvije veličine: indeks stanja kandidata, te indeks važnosti u EES-u kandidata za revitalizaciju.

Obje veličine izračunavaju se uključivanjem odgovarajućih kriterija u jedinstvenu funkciju pri čemu se važnost pojedinih kriterija definira odgovarajućim težinskim faktorima (oznaka w). Težinski faktori se određuju subjektivno, na temelju procjene operatora prijenosnog sustava i važnosti koju on daje pojedinim kriterijima. Ovisnost liste prioriteta za revitalizaciju o težinskim faktorima moguće je naknadno ispitivati analizom osjetljivosti, varirajući ih u određenom rasponu.

6.1 Indeks stanja kandidata za revitalizaciju

Indeks stanja kandidata za revitalizaciju (oznaka ZiR_{k_st}) izračunava se na temelju promatranih kriterija ovisnih o stvarnom stanju promatrane jedinice, na način da su za pojedine kriterije (starost, neraspoloživost, troškovi održavanja) promatrane veličine normalizirane (izražene kao omjer između promatrane veličine za neki kandidat i najveće promatrane veličine u toj kategoriji uzimajući u obzir sve kandidate), a zatim pomnožene s određenim težinskim faktorima te zbrojene. Za pojedine kriterije nisu kvantificirane veličine kojima bi ih jednoznačno mogli definirati (rezultati pregleda i dijagnostike jedinice, tehničko stanje jedinica i ostali pokazatelji), pa se postupa na način da operator prijenosnog sustava subjektivno pridružuje vrijednosti između 0 i 1 promatranim kriterijima, pri čemu se vrijednost 1 pridružuje onim kandidatima kod kojih je stanje utvrđeno vizualnim pregledom ili dijagnostikom potpuno nezadovoljavajuće, ili tehničko stanje ili ostali pokazatelji stanja potpuno su nezadovoljavajući, dok se vrijednost 0 pridružuje onim kandidatima kod kojih je stanje utvrđeno vizualnim pregledom ili dijagnostikom potpuno zadovoljavajuće, i tehničko stanje ili ostali pokazatelji stanja su potpuno zadovoljavajući. Matematički indeks stanja kandidata k za revitalizaciju formulira se na sljedeći način:

bine all the criteria and compile a common priority list. For that reason two values are defined: the condition index of candidates and the index of the EPS significance of revitalization candidates.

Both values are calculated by including appropriate criteria in a single function, where the importance of individual criteria is defined by related weighting factors (sign w). The weighting factors are defined subjectively, by personal judgment of the transmission system operator and based on the importance the operator attaches to particular criteria. The dependence of the revitalization priority list on the weighting factors can be subsequently examined by a sensitivity analysis, varying them within a certain range.

6.1 Condition index of revitalization candidates

The condition index of revitalization candidates (denoted ZiR_{k_st}) is computed on the basis of the observed criteria dependent on the real condition of the observed unit, in such a way that for particular criteria (age, unavailability, maintenance costs) the observed values are normalized (expressed as a ratio between the observed value for a candidate and the greatest observed value in that category, with all the candidates taken into consideration) and then multiplied with appropriate weighting factors and summed up. For certain criteria values are not quantified by which they could be clearly defined (inspection and diagnostic results, the technical condition of units and other indicators), so the transmission system operator subjectively assigns values between 0 and 1 to the observed criteria, with value 1 being assigned to those candidates where by visual inspection or diagnostics the status has been found as entirely unsatisfactory, or the technical status or other status indices are entirely unsatisfactory, and value 0 being assigned to those candidates where by visual inspection or diagnostics the status has been found as entirely satisfactory, and the technical status or other status indices have been found as entirely satisfactory as well. The mathematical condition index of revitalization candidates k is formulated as follows:

$$ZiR_{\mathrm{k\_st}} = w_{\mathrm{s}1}\cdot\frac{\dfrac{T_{\mathrm{k}}}{T}}{Max\left\{\dfrac{T_{\mathrm{k}}}{T}\right\}} + w_{\mathrm{s}2}\cdot\frac{\dfrac{q_{\mathrm{k}}}{q_J}}{Max\left\{\dfrac{q_{\mathrm{k}}}{q_J}\right\}} + w_{\mathrm{s}3}\cdot\frac{\dfrac{C_m(\mathrm{k})}{C_{pm}(k)}}{Max\left\{\dfrac{C_m(\mathrm{k})}{C_{pm}(\mathrm{k})}\right\}} + w_{\mathrm{s}4}\cdot VID + w_{\mathrm{s}5}\cdot TS, \qquad (41)$$

pri čemu je:

$ZiR_{\mathrm{k\_st}}$ – indeks stanja kandidata za revitalizaciju k,
$w_{\mathrm{s}1}$ – težinski faktor pridružen kriteriju starosti kandidata $(0 \le w_{\mathrm{s}1} \ge 0{,}2)$,

where:

$ZiR_{\mathrm{k\_st}}$ – condition index of revitalization candidates k,
$w_{\mathrm{s}1}$ – weighting factor assigned to the criterion of

w_{s2} – težinski faktor pridružen kriteriju neraspoloživosti kandidata ($0 \leq w_{s2} \geq 0{,}2$),
w_{s3} – težinski faktor pridružen kriteriju troškova održavanja kandidata ($0 \leq w_{s3} \geq 0{,}2$),
w_{s4} – težinski faktor pridružen kriteriju rezultata vizualne inspekcije i dijagnostičkih pregleda ($0 \leq w_{s4} \geq 0{,}2$),
w_{s5} – težinski faktor pridružen kriteriju tehničkog stanja i ostalih pokazatelja stanja ($0 \leq w_{s5} \geq 0{,}2$),
VID – subjektivno određena ocjena vizualne inspekcije i dijagnostičkih pregleda ($0 \leq VID \geq 1$),
TS – subjektivno određena ocjena tehničkog stanja i ostalih pokazatelja stanja ($0 \leq TS \geq 1$).

Svi razlomci u gornjem izrazu poprimaju vrijednosti između 0 i 1, kao i subjektivno određene veličine VID i TS, a da bi se omogućila usporedba i jednako tretiranje indeksa stanja i indeksa važnosti u EES-u kandidata za revitalizaciju, svi pojedinačni težinski faktori moraju biti određeni u rasponu od 0 do 0,2. Uz tako određene težinske faktore maksimalan mogući indeks stanja iznosi 1.

6.2 Indeks važnosti u EES-u kandidata za revitalizaciju

Indeks važnosti u EES-u kandidata za revitalizaciju (oznaka ZiR_{k_zn}) izračunava se na temelju pet promatranih kriterija ovisnih o ulozi i važnosti jedinice unutar sustava, na način da su razlike troškova za pojedine kriterije normalizirane (izražene kao omjer između razlike troškova pojedinog kandidata i maksimalne razlike troškova u promatranoj kategoriji za sve kandidate), a zatim pomnožene s određenim težinskim faktorima te zbrojene. Kandidati su poredani prema padajućim vrijednostima tako zbrojenih veličina. Matematički se to može izraziti na sljedeći način:

the candidate's age ($0 \leq w_{s1} \geq 0{,}2$),
w_{s2} – weighting factor assigned to the criterion of the candidate's unavailability ($0 \leq w_{s2} \geq 0{,}2$),
w_{s3} – weighting factor assigned to the criterion of the candidate's maintenance costs ($0 \leq w_{s3} \geq 0{,}2$),
w_{s4} – weighting factor assigned to the criterion of the results of visual inspection and diagnostic examinations ($0 \leq w_{s4} \geq 0{,}2$),
w_{s5} – weighting factor assigned to the criterion of the technical status and other status indices ($0 \leq w_{s5} \geq 0{,}2$),
VID – subjective evaluation of visual inspection and diagnostic examinations ($0 \leq VID \geq 1$),
TS – subjective evaluation of the technical status and other status indices ($0 \leq TS \geq 1$).

All fractions in the above expression assume values between 0 and 1, and so do the subjectively assessed values VID and TS. In order to ensure the comparison and equal treatment of condition index and significance index of the revitalization candidates in the EPS, all individual weighting factors must be defined within a range of 0 to 0,2. With the weighting factors thus defined, the maximum possible condition index amounts to 1.

6.2 EPS significance index of the revitalization candidates

The EPS significance index of the revitalization candidates (denoted ZiR_{k_zn}) is computed on the basis of five observed criteria dependent on the role and importance of the observed unit, in such a way that for particular criteria the observed values are normalized (expressed as a ratio between the cost difference for a candidate and the maximum cost difference in the observed category for all candidates) and then multiplied with appropriate weighting factors and summed up. The candidates are arranged in the descending order of the thus summed up values. Mathematically it can be expressed as follows:

$$
\begin{aligned}
ZiR_{k\_zn} = {} & w_{z1} \cdot \frac{\overline{OC_i(j) - OC_{i,k}(j)}}{Max\{OC_i(j) - OC_{i,k}(j)\}} + w_{z2} \cdot \frac{\overline{OC_i(j) - OC'_{i,k}(j)}}{Max\{OC_i(j) - OC'_{i,k}(j)\}} + \\
& w_{z3} \cdot \frac{\overline{OC_{i,k1}(j) - OC_{i,k}(j)}}{Max\{OC_{i,k1}(j) - OC_{i,k}(j)\}} + w_{z4} \cdot \frac{\overline{OC_{i,k1}(j) - OC_{i,k0}(j)}}{Max\{OC_{i,k1}(j) - OC_{i,k0}(j)\}} + \\
& w_{z5} \cdot \frac{\overline{MC_{i,k}(j)}}{Max\{MC_{i,k}(j)\}}
\end{aligned}
, \qquad (42)
$$

pri čemu je:

ZiR_{k_zn} - indeks značaja u EES-u kandidata k,

w_{z1} - težinski faktor pridružen starosnom kriteriju ($0 \leq w_{z1} \geq 0{,}2$),

w_{z2} - težinski faktor pridružen ekonomskom kriteriju ($0 \leq w_{z2} \geq 0{,}2$),

w_{z3} - težinski faktor pridružen kriteriju opasnosti od trajnog otkaza ($0 \leq w_{z3} \geq 0{,}2$),

w_{z4} - težinski faktor pridružen kriteriju važnosti u elektroenergetskom sustavu ($0 \leq w_{z4} \geq 0{,}2$),

w_{z5} - težinski faktor pridružen kriteriju maksimalne marginalne dobiti ($0 \leq w_{z5} \geq 0{,}2$).

Svi razlomci u gornjem izrazu poprimaju vrijednosti između 0 i 1, a da bi se omogućilo usporedbu i jednako tretiranje indeksa stanja i indeksa značaja u EES-u kandidata za revitalizaciju, svi pojedinačni težinski faktori moraju biti određeni u rasponu od 0 do 0,2. Uz tako određene težinske faktore maksimalan mogući indeks važnosti u EES-u iznosi 1.

Indeksi važnosti u EES-u kandidata za revitalizaciju ovisni su o iznosima neraspoloživosti svih grana u mreži, tako da promjena neraspoloživosti bilo koje grane dovodi do drugačijih rezultata i u konačnici utječe na listu prioriteta za revitalizaciju ostalih kandidata u mreži. Da bi se dobili točniji rezultati bilo bi nužno iterativno ponavljati čitav proces prethodno opisan, s novim vrijednostima neraspoloživosti grana nakon njihove revitalizacije. Tako bi, na primjer, trebalo nakon revitalizacije prvog kandidata s liste prioriteta procijeniti njegovu novu neraspoloživost, ponoviti sve proračune i odrediti novu listu prioriteta, što najčešće neće biti moguće napraviti zbog velikog broja proračuna. Iskustveno se može reći da su najviše međuovisni električki bliski vodovi, pogotovo oni koji napajaju isto čvorište mreže. Promjena neraspoloživosti jednog takvog voda utječe na indeks važnosti u EES-u ostalih kandidata za revitalizaciju, a time i na mjesto na listi prioriteta za drugi električki bliski kandidat, ali ne mijenja iznose indeksa važnosti u EES-u za ostale kandidate, pogotovo za one električki udaljene od svih kandidata prethodnih na listi.

6.3 Jedinstvena lista prioriteta za revitalizaciju

Konačna i jedinstvena lista prioriteta određuje se na temelju maksimalnog zbroja indeksa stanja i indeksa važnosti kandidata za revitalizaciju.

where:

ZiR_{k_zn} - EPS significance index of candidates k,

w_{z1} - weighting factor assigned to the age criterion ($0 \leq w_{z1} \geq 0{,}2$),

w_{z2} - weighting factor assigned to the economic criterion ($0 \leq w_{z2} \geq 0{,}2$),

w_{z3} - weighting factor assigned to the criterion of the risk of permanent failure ($0 \leq w_{z3} \geq 0{,}2$),

w_{z4} - weighting factor assigned to the criterion of EPS relevancy ($0 \leq w_{z4} \geq 0{,}2$),

w_{z5} - weighting factor assigned to the criterion of maximum marginal gain ($0 \leq w_{z5} \geq 0{,}2$).

All fractions in the above expression assume values between 0 and 1. In order to ensure the comparison and equal treatment of condition index and significance index of the revitalization candidates in the EPS, all individual weighting factors must be defined within a range of 0 to 0,2. With the weighting factors thus defined, the maximum possible significance index amounts to 1.

The EPS significance index of the revitalization candidates depend on the unavailability of all branches in the network, so that a change in unavailability of any branch leads to different results and in the end affecting the revitalization priority list of other candidates in the network. In order to obtain more accurate results, it would be necessary to iterate the whole above described process, with new unavailability values of the branches following their revitalization. Thus, for example, after the revitalization of the first candidate on the priority list it would be necessary to assess the candidate's new priority list, which will be virtually impossible to do because of numerous calculations. Experience tells us that electrically close lines are most interdependent, especially those feeding the same network node. A change in the unavailability of such a line affects the EPS significance index of other revitalization candidates and thereby also the place on the priority list of the other electrically close candidate, but it does not change the EPS significance index amounts for other candidates, especially those electrically remote from all the candidates higher on the list.

6.3 An integrated revitalization priority list

The final and integrated priority list is compiled on the basis of the maximum sum of condition index and significance index of the revitalization candidates.

$$ZiR_{k} = Max\left\{ZiR_{k\_st} + ZiR_{k\_zn}\right\} \quad . \tag{43}$$

Maksimalan iznos koji može poprimiti veličina ZiR_k je 2, pri čemu se kandidati za revitalizaciju popisuju prema padajućim vrijednostima veličine ZiR_k. Najvažniji kandidat za revitalizaciju je onaj s maksimalnim iznosom ZiR_k.

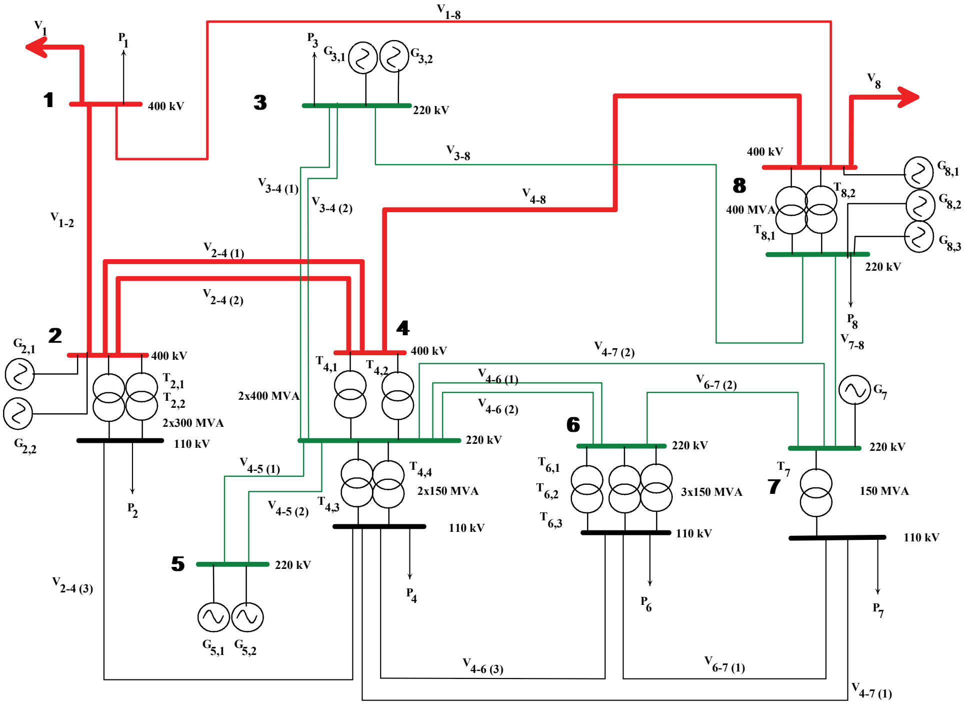
7 PRIMJER

Opisana metodologija za određivanje liste prioriteta za revitalizaciju vodova i transformatora u prijenosnim mrežama provjerena je na test modelu EES-a. Test model EES-a prikazan je slikom 3. Prijenosna se mreža sastoji od 400 kV (crveno), 220 kV (zeleno) i 110 kV (crno) naponskih razina. U mreži ima ukupno 19 vodova, 12 transformatora, 7 potrošača i 10 generatora. Od ukupno 31 grane, 10 vodova i transformatora starije je od 40 godina.

Maximum amount that the value ZiR_k can assume is 2, with the revitalization candidates being listed in the descending order of values ZiR_k. The most relevant revitalization candidate is one with a maximum amount of ZiR_k.

7 EXAMPLE

The described methodology for compiling a revitalization priority list of lines and transformers in transmission networks has been checked on the EPS Test Model. The EPS Test Model is shown in Figure 3. The transmission network consists of 400 kV (red), 220 kV (green) and 110 kV (black) voltage levels. In the network there are altogether 19 lines, 12 transformers, 7 consumers and 10 generators. Out of 31 branches, 10 lines and transformers are older than 40 years.



Slika 3 — Test model EES-a

Figure 3 — EPS Test Model

U čvorištima 1 i 8 priključeni su interkonektivni 400 kV vodovi prema susjednim EES-ima za koje se pretpostavlja da omogućavaju uvoz određene snage po definiranoj cijeni tijekom čitave godine. Susjedni EES-i u proračunima su ekvivalentirani nadomjesnim generatorima (elektranama). Pretpostavlja se da je svakim od interkonektivnih vodova prema susjednim sustavima moguće tijekom čitave godine uvoziti maksimalno 1 000 MW u interventnim situacijama po cijeni od 5,5 EURc/kWh.

In nodes 1 and 8 interconnection 400 kV lines are connected towards the neighboring EPS's presumed to allow the import of a certain power at a defined price throughout the year. The neighboring EPS's are in the calculations replaced with equivalent generators (power plants). It is presumed that with each of the interconnection lines towards the neighboring systems it is possible throughout the year to import a maximum of 1 000 MW in emergencies at a price of 5,5 EURc/kWh.

Mreža se sastoji od pet 400 kV vodova, deset 220 kV i četiri 110 kV voda. Vodovi su određeni svojim uzdužnim impedancijama (radnim otporom (R) i reaktancijom (X)), maksimalno dozvoljenom trajnom strujom u normalnom pogonu (I_{max}), te svojom neraspoloživošću (q). Neraspoloživost radi prisilnih i planiranih zastoja odgovara aritmetičkoj sredini ostvarenih vrijednosti u promatranom desetogodišnjem razdoblju. Za vodove starije od 40 godina izvršena je procjena neraspoloživosti u budućem trogodišnjem razdoblju postupkom opisanim u poglavlju 3.

U mreži postoji ukupno četiri transformatora 400/220 kV snage 400 MVA, dva transformatora 400/110 kV snage 300 MVA, te šest transformatora 220/110 kV snage 150 MVA svaki. Transformatori su određeni svojim radnim otporom (R), reaktancijom (X), prividnom snagom (S), te svojom neraspoloživošću (q). Neraspoloživost radi prisilnih i planiranih zastoja odgovara aritmetičkoj sredini ostvarenih vrijednosti u promatranom desetogodišnjem razdoblju. Za transformatore starije od 40 godina izvršena je procjena neraspoloživosti u budućem trogodišnjem razdoblju postupkom opisanim u poglavlju 3.

Ukupno vršno opterećenje za razmatrane vremenske presjeke (razdoblje $t_1 - t_3$) iznosi redom:

$P_{max}(t_1) = 2\,094$ MW,
$P_{max}(t_2) = 2\,125$ MW,
$P_{max}(t_3) = 2\,157$ MW.

Raspodjela vršnog opterećenja po pojedinim čvorištima također je zadana. Zadane su i godišnje krivulje trajanja opterećenja u godini t_1, t_2 i t_3. Krivulje su podijeljene na pet dijelova i aproksimirane pravcima. Svaki od pojedinih dijelova godišnje krivulje trajanja opterećenja određen je srednjom vrijednošću opterećenja u megavatima i njegovim trajanjem u satima. Pojedinim dijelovima krivulja trajanja opterećenja pridružene su različite neraspoloživosti grana. Neraspoloživost radi prisilnih zastoja pridružena je dijelovima krivulje karakterističnim po vršnom opterećenju, te visokim i niskim zimskim opterećenjima, dok je ukupna neraspoloživost pridružena dijelovima krivulje karakterističnim po visokim i niskim ljetnim opterećenjima.

Na modelu elektroenergetskog sustava nalazi se šest elektrana od kojih su dvije nuklearne (NE, čvorišta 2 i 8), dvije su plinske kombi termoelektrane (KTE, čvorište 7 i čvorište 8), jedna termoelektrana-toplana (TE-TO, čvorište 3), te jedna akumulacijska hidroelektrana u čvorištu 5. Elektranama su poznate maksimalne snage na pragu, troškovi proizvodnje (goriva), te raspoloživost generatora koju određuju planirani i neplanirani zastoji. Akumulacijskoj hidroelektrani poznata je

The network consists of five 400 kV lines, ten 220 kV and four 110 kV lines. The lines are defined by their impedances (resistance (R) and reactance (X)), maximum permissible permanent current in normal operation (I_{max}), and their unavailability (q). Unavailability due to forced and planned outages corresponds to the arithmetic mean of realized values in the observed 10-year period. For the lines older than 40 years an assessment of unavailability in the future 3-year period has been made by applying the procedure described in section 3.

In the network there are altogether four 400/220 kV transformers of 400 MVA, two 400/110 kV transformers of 300 MVA, and six 220/110 kV transformers of 150 MVA power level each. The transformers are defined by their resistance (R), reactance (X), rated power (S) as well as their unavailability (q). Unavailability due to forced and planned outages corresponds to the arithmetic mean of realized values in the observed 10-year period. For transformers older than 40 years an assessment of unavailability in the future 3-year period has been made by applying the procedure described in section 3.

The total peak load for the examined time cross-sections (period $t_1 - t_3$) amounts in the ascending order:

$P_{max}(t_1) = 2\,094$ MW,
$P_{max}(t_2) = 2\,125$ MW,
$P_{max}(t_3) = 2\,157$ MW.

The peak load distribution by nodes is also given, and so are the annual load duration curves in year t_1, t_2 and t_3. The curves are divided into five parts and straight line approximated. Each of the parts of the annual load duration curve is defined by the mean value of load in megawatts and its duration in hours. To the particular parts of the load duration curves various branch unavailabilities are attached. Unavailability due to forced outages is attached to the parts of the curve characterized by their by peak load and high and low winter loads, whereas the total unavailability is attached to the parts of the curve characterized by high and low summer loads.

On the EPS model there are six power plants of which two are nuclear (NPP, nodes 2 and 8), two are combined-cycle power plants (CCGT, node 7 and node 8), one is a combined heat and electricity production power plant (CHP, node 3), and one is a storage hydro plant in node 5. Known about the power plants are installed powers, costs of generation (fuel) and the generator availability defined by planned and unplanned outages. Known about the storage hydro plant are installed power and engagement corresponding to zero generation costs.

instalirana snaga i angažmanom koji odgovara nultim troškovima proizvodnje.

Polazni angažman akumulacijske hidroelektrane (HE) u čvorištu 5 određen je na osnovi prosječnih mjesečnih dotoka u promatranom razdoblju. Tako određena angažirana snaga hidroelektrane predstavlja gornju granicu proizvodnje uz troškove jednake nuli, pa će svaki dodatni angažman akumulacijske hidroelektrane (u slučaju preraspodjele proizvodnje na modelu radi izbjegavanja preopterećenja pojedinih grana prijenosne mreže) značiti povećanje troškova dodatne hidro proizvodnje i ukupnih troškova rada sustava. Neplanirano pražnjenje akumulacije u tom slučaju donosi dodatni trošak koji je procijenjen na 5 EURc/kWh, što znači da će se eventualno preopterećenje pojedine grane mreže pokušati izbjeći preraspodjelom termo proizvodnje u sustavu, a tek onda dodatnim pražnjenjem akumulacije hidroelektrane u čvorištu 5.

Vjerojatnosti nastanka pojedinih hidroloških stanja iznose:

— normalna hidrologija: $q_{nh} = 0{,}5$,
— suha hidrologija: $q_{sh} = 0{,}2$,
— vlažna hidrologija: $q_{vh} = 0{,}3$.

U slučaju nemogućnosti otklanjanja preopterećenja u mreži, algoritam računa minimalno potrebnu redukciju opterećenja kako bi sve grane mreže ostale opterećene unutar dozvoljenih granica. Redukcija opterećenja izaziva određeni trošak, a kao jedinični trošak neisporučene električne energije definirana je vrijednost od 3 EUR/kWh.

Kandidati za zamjene i rekonstrukcije su (jedinice starije od 40 godina):

$V_{3-4(1)}$ – 220 kV vod između čvorišta 3 i 4,
V_{3-8} – 220 kV vod između čvorišta 3 i 8,
$V_{4-7(2)}$ – 220 kV vod između čvorišta 4 i 7,
$V_{6-7(2)}$ – 220 kV vod između čvorišta 6 i 7,
$V_{4-6(3)}$ – 110 kV vod između čvorišta 4 i 6,
$V_{6-7(1)}$ – 110 kV vod između čvorišta 6 i 7,
$T_{4,3}$ – 220/110 kV transformator u čvorištu 4,
$T_{4,4}$ – 220/110 kV transformator u čvorištu 4 (paralelan prethodnom),
$T_{6,1}$ – 220/110 kV transformator u čvorištu 6,
T_7 – 220/110 kV transformator u čvorištu 7.

Za svaki promatrani vremenski presjek formirana su tri scenarija ovisna o hidrologiji (normalna, suha i vlažna hidrologija). Ukupno je analizirano 9 scenarija unutar promatrana tri vremenska razdoblja te su izvršene probabilističke simulacije rada sustava za različite visine neraspoloživosti pojedinih grana kandidata za revitalizaciju.

The starting engagement of the storage hydro plant (HPP) in node 5 is defined on the basis of average monthly inflows over the observed period. The engaged power of a hydro plant thus defined represents the upper limit of generation at zero cost, so each additional engagement of a storage hydro plant (in case of generation redistribution on the model in order to avoid overloads of particular transmission network branches) will entail an increase in the cost of additional hydro generation and the overall system operation costs. Unplanned discharging of the storage in that case brings with it an additional cost estimated at 5 EURc/kWh, meaning that an attempt will be made to avoid overloading a branch through redistribution of thermo generation in the system and only then by additional discharging of the hydro plant storage in node 5.

The probabilities of the occurrence of particular hydrological conditions are:

— normal hydrology: $q_{nh} = 0{,}5$,
— dry hydrology: $q_{sh} = 0{,}2$,
— wet hydrology: $q_{vh} = 0{,}3$.

If it is impossible to eliminate overloads in the network, the algorithm computes minimum required load reduction so that all branches may stay loaded within permissible margins. Load reduction involves a certain cost. The value of 3 EUR/kWh is defined as the unit cost of undelivered electricity.

Replacement and reconstruction candidates are (units older than 40 years):

$V_{3-4(1)}$ – 220 kV line between nodes 3 and 4,
V_{3-8} – 220 kV line between nodes 3 and 8,
$V_{4-7(2)}$ – 220 kV line between nodes 4 and 7,
$V_{6-7(2)}$ – 220 kV line between nodes 6 and 7,
$V_{4-6(3)}$ – 110 kV line between nodes 4 and 6,
$V_{6-7(1)}$ – 110 kV line between nodes 6 and 7,
$T_{4,3}$ – 220/110 kV transformer in node 4,
$T_{4,4}$ – 220/110 kV transformer in node 4 (parallel to the previous one),
$T_{6,1}$ – 220/110 kV transformer in node 6,
T_7 – 220/110 kV transformer in node 7.

For each observed time cross-section three scenarios are defined, depending on the hydrological conditions (normal, dry and wet hydrology). A total of 9 scenarios have been analyzed with the observed three-year period of time and the probabilistic system operation simulations have been carried out for different unavailability levels of the particular branches of the revitalization candidates.

Tablica 2 – Prosječno povećanje očekivanih godišnjih operativnih troškova rada EES-a radi slabosti mreže uz različite iznose neraspoloživosti kandidata za revitalizaciju (EUR)
Table 2 – Average increase in the expected annual operating costs of the EPS due to the weaknesses of the network, at different levels of unavailability of the revitalization candidates (EUR)

Kandidati za *ZiR* / Candidates for revitalization	$\overline{OC_i(j) - OC_{i,k}(j)}$	$\overline{OC_i(j) - OC'_{i,k}(j)}$	$\overline{OC_{i,k1}(j) - OC_i(j)}$	$\overline{OC_{i,k1}(j) - OC_{i,k0}(j)}$	$\overline{M_{i,k}(j)}$
$V_{3-4(1)}$	0	0	2 949	2 949	0
V_{3-8}	4	4	7 984	7 988	0
$V_{4-7(2)}$	0	0	5 686	5 704	7
$V_{6-7(2)}$	0	0	23	23	0
$V_{4-6(3)}$	0	0	122 092	122 092	0
$V_{6-7(1)}$	0	119	86 276	88 045	0
$T_{4,3}$	537	537	1 541 123	1 541 044	205
$T_{4,4}$	25	25	1 422 160	1 422 245	0
$T_{6,1}$	497	497	1 961 804	1 962 301	0
T_7	1 859	1 859	1 452 287	1 454 145	0
Max	1 859	1 859	1 961 804	1 962 301	205

Tablica 2 prikazuje prosječna povećanja očekivanih godišnjih operativnih troškova rada EES-a radi slabosti mreže za sve ispitane scenarije ovisne o razmatranom vremenskom presjeku i hidrološkom stanju uz različite iznose neraspoloživosti kandidata za revitalizaciju, uvažavajući pri tom vjerojatnosti nastanka pojedinih hidroloških stanja. U zadnjem retku tablice prikazane su maksimalne vrijednosti u pojedinim razmatranim kategorijama.

Jedinstvena lista prioriteta za zamjene i rekonstrukcije izrađuje se na temelju izraza (43). Svi težinski faktori postavljeni su na iznos od 0,2. Listu prioriteta prikazuje tablica 3. Najvažniji kandidat za revitalizaciju prema kriterijima i metodologiji razvijenoj u ovom radu je 220/110 kV transformator 3 u čvorištu 4. Zbroj pripadnih indeksa stanja i važnosti u EES-u za ovaj transformator iznosi 1,137 od ukupno mogućeg najvećeg zbroja od 2. Slijedi ga 220/110 kV transformator u čvorištu 7 sa zbrojem indeksa stanja i važnosti od 1,131. Zadnji na listi prioriteta je 220 kV vod između čvorišta 6 i 7.

Table 2 shows the average increases in the expected annual operating costs of the EPS due to the weaknesses of the network for all tested scenarios dependent on the reviewed time cross-section and the hydrological conditions at different levels of the unavailability of the revitalization candidates, with the probabilities of the occurrence of particular hydrological conditions being taken into consideration. In the last row of the above table the maximum values by studied categories are shown.

The integrated revitalization priority list is compiled on the basis of expression (43). All weighting factors are set on the amount of 0,2. The priority list is shown in Table 3. The most important revitalization candidate according to the criteria and methodology developed in this work is the 220/110 kV transformer 3 in node 4. The sum of the related condition and the EPS significance indices for that transformer amounts to 1,137 out of the highest possible sum of 2. It is followed by the 220/110 kV transformer in node 7 with the sum of the condition and significance indices amounting to 1,131. The last on the priority list is the 220 kV line between nodes 6 and 7.

Tablica 3 – Konačna lista prioriteta za revitalizaciju (test model EES)
Table 3 – Final revitalization priority list (EPS Test Model)

Kandidati za *ZiR* / Candidates for revitalization	ZiR_k	Poredak / Order
$T_{4,3}$	1,137	1
T_7	1,131	2
$T_{6,1}$	0,909	3
$V_{4-6(3)}$	0,831	4
$V_{6-7(1)}$	0,740	5
$T_{4,4}$	0,605	6
$V_{4-7(2)}$	0,401	7
$V_{3-4(1)}$	0,358	8
$V_{6-7(2)}$	0,287	9
V_{3-8}	0,243	10

8 ZAKLJUČAK

Pristup određivanju liste prioriteta za revitalizaciju vodova i transformatora u prijenosnoj mreži, predložen ovim istraživanjem, različit je od pristupa drugih istraživača objavljenih u dostupnoj literaturi. Osnovna karakteristika predloženog postupka i njegova prednost u odnosu na ostale metode je što nastoji integrirati rezultate dijagnostike i ispitivanja stvarnog stanja jedinica prijenosne mreže i njihove uloge u toj mreži, određene na temelju probabilističkih simulacija rada EES-a i očekivanih troškova njegova rada pri različitim razinama neraspoloživosti promatranih jedinica, u jedinstveni skup te na osnovi postavljenih kriterija i metodologije istraživanja odrediti jedinstvenu listu prioriteta za revitalizaciju.

Na taj se način na temelju troškovnih principa, tehničkih karakteristika, stohastičke prirode EES-a i statističkih podataka određuje optimalan plan revitalizacije kapitalne opreme u prijenosnoj mreži, kao što su vodovi i transformatori, te doprinosi povećanju pouzdanosti rada EES-a, kao i sigurnosti opskrbe potrošača električnom energijom.

Predloženom metodom također se unaprjeđuje postupak planiranja razvoja prijenosnih elektroenergetskih mreža, budući da u dosadašnjim metodama nije u obzir uziman aspekt starosti opreme u prijenosnoj mreži. Također se omogućava sagledavanje eventualnih potreba za izmjenom karakteristika pojedine opreme kroz aktivnosti na revitalizaciji, a ovisno o budućim potrebama EES-a. Na taj se način pridonosi boljem iskorištenju postojećih koridora i ubla-

8 CONCLUSION

The approach to the priority list to be defined for the revitalization of lines and transformers in a transmission network proposed in the present research differs from the approach advocated by other researchers in the accessible literature. The basic feature of the proposed procedure and its advantage in relation to other methods is that it tries to integrate the results of the diagnostics and testing of the real condition of the transmission network units and their role in the network, defined on the basis of probabilistic simulations of the EPS's operation and the expected costs of its operation at different unavailability levels of the observed units, into a common group and, based on the set criteria and investigation methodology, to define a single revitalization priority list.

In this way, based on cost principles, technical characteristics, the stochastic nature of the EPS and statistics, an optimum plan for the revitalization of capital equipment in the transmission network, such as the lines and transformers, is defined, and a contribution made to an increased operating reliability of the EPS, as well as to the security of supplying consumers with electricity.

The proposed method also improves the procedure of planning the development of electric power transmission networks, because the existing methods do not make allowance for the age aspect of transmission network equipment. What is also made possible is identifying likely needs for modification of the characteristics of some equipment through revitalization activities and in dependence on the EPS's future needs. In this way it is contributed to žavanju prostornih ograničenja koji zbog porasle ekološke svijesti predstavljaju sve veći problem u razvoju EES-a.

Metodologija i kriteriji definirani u ovom radu predstavljaju doprinos rješavanju problema izrade jedinstvene liste prioriteta zamjene i izgradnje jedinica mreže u uvjetima neizvjesnosti koji postoje unutar otvorenih tržišta električnom energijom.

better utilization of the existing corridors aimed to mitigate the effect of spatial constraints which, due to raised environmental awareness, pose an increasing problem to the EPS development.

The methodology and the criteria defined in the present work are meant to be a useful tool in addressing the problem of compiling an integrated priority list of replacement and construction of network units under the conditions of uncertainty existing on open electricity markets.

LITERATURA / REFERENCES

[1] CIGRÉ WG 37-27, Ageing of the System – Impact on Planning, Paris, 2000

[2] Comparison of Overhead Lines and Underground Cables for Electricity Transmission, Joint Working Group 21/22-01, CIGRE, Paris, 1996

[3] RADAKOVIC, Z., CARDILLO, E., FESER, K., The Influence of Transformer Loading to the Ageing of the Oil-paper Insulation, XIII International Symposium on High Voltage Engineering, Netherlands, 2003

[4] YAO, Z. T., SAHA, T. K., Separation of Ageing and Moisture Impacts on Transformer Insulation Degradation by Polarization Measurements, Cigre session 2002, Paris, 2002

[5] REICHELT, D., FREY, A., SCHONENBERGER, M., Life Expectancy of Power System Apparatus and Components, Cigre session 1996, Paris, 1996

[6] Statistika pogonskih događaja u prijenosnoj mreži (1995. – 2006.), HEP-OPS d.o.o., Zagreb, 1996. – 2007.

[7] WILLIS, H. LEE., WELCH, G. V., SCHRIEBER, R. R., Aging Power Delivery Infrastructures, Marcel Dekker, Inc., 2001

[8] WENYUAN LI, Incorporating Aging Failures in Power System Reliability Evaluation, IEEE Transactions on Power Systems, Vol. 17, No. 3, August 2002

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KRATKOROČNO PROGNOZIRANJE OPTEREĆENJA PRIMJENOM MODELA UMJETNE NEURONSKE MREŽE

SHORT-TERM LOAD FORECASTING BY USING THE ARTIFICIAL NEURAL NETWORK MODEL

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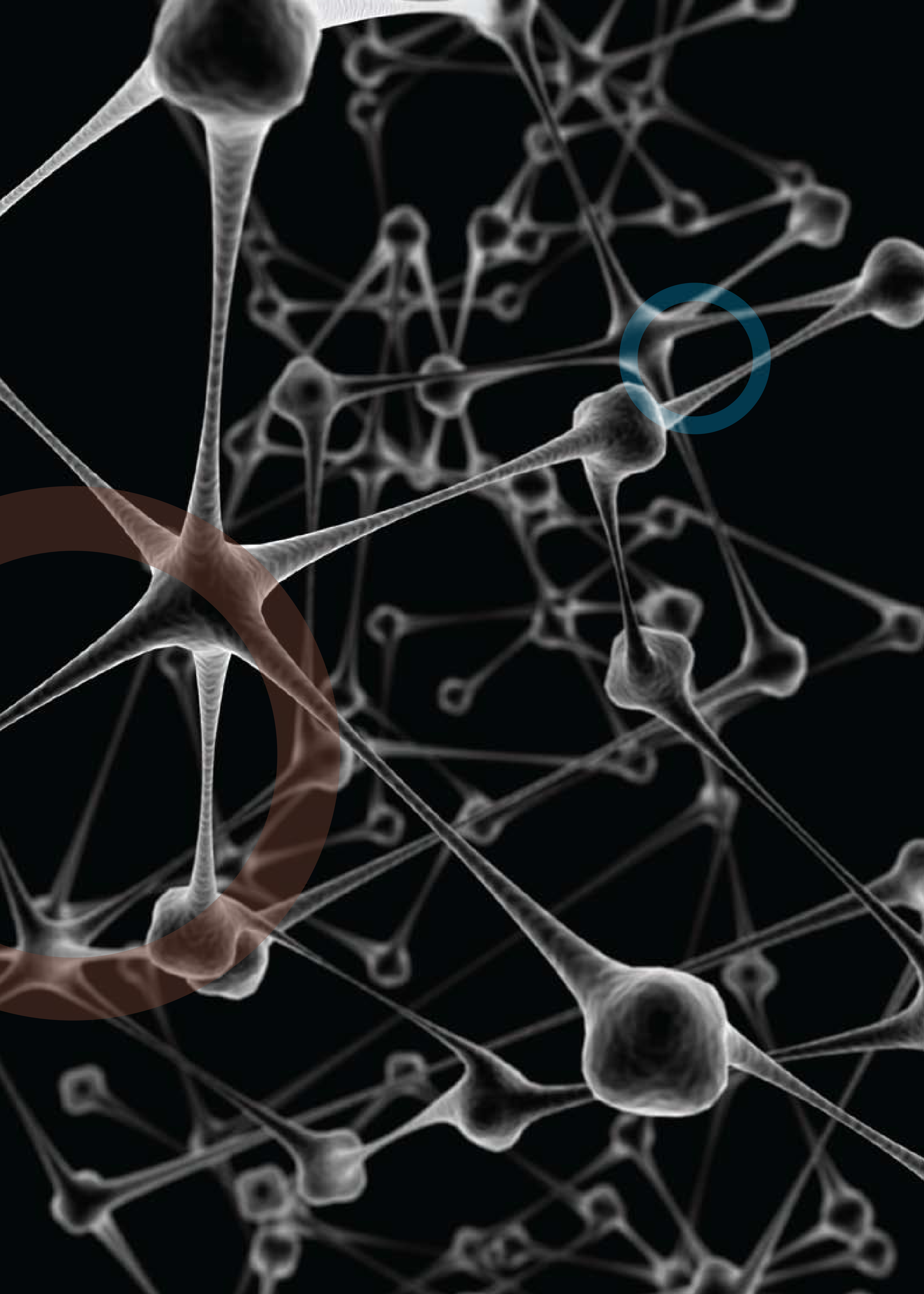
U članku je opisan model za kratkoročnu prognozu opterećenja primjenom umjetne neuronske mreže i njegova primjena na predviđanje opterećenja jednog konkretnog distribucijskog područja. Umjetne neuronske mreže koriste se najčešće za rješavanje problema klasifikacije i predviđanja kada su odnosi između ulaznih i izlaznih varijabli vrlo složeni i egzaktno teško opisivi. S obzirom na stohastičku prirodu i veliki utjecaj vremenskih prilika (temperatura, vlažnost, vjetar i dr.) na potrošnju električne energije, primjena umjetnih neuronskih mreža prikladna je za kratkoročno predviđanje opterećenja elektroenergetskog sustava. U članku su opisani korišteni modeli umjetnih neuronskih mreža za sezonsku i višestruku dnevnu prognozu opterećenja, te su prikazani rezultati predviđanja opterećenja jednog distribucijskog područja napajanog preko sabirnica transformatorske stanice $110/x$ u HEP Operator distribucijskog sustava Elektroslavonija (HEP ODS).

The article describes a model for short-term load forecasting by using the artificial neural network, and its application to load forecasting for a concrete distribution area. The artificial neural networks are mostly used in solving the problems of classification and prediction when the relations between input and output variables are highly complex and hard to describe exactly. Considering the stochastic nature and the major impact of weather conditions (temperature, humidity, wind, etc.) on electricity consumption, the application of artificial neural networks is suitable for short-term forecasting the load of an electric power system (EPS). Furthermore, the article describes the used models of artificial neural networks for seasonal and multiple daily load forecasts and presents the load forecast results for a distribution area supplied over the busbars of the $110/x$ substation at the HEP Elekroslavonija Distribution System Operator (HEP ODS).

Ključne riječi: kratkoročna prognozira opterećenja; modeli prognoziranja; umjetne neuronske mreže
Keywords: artificial neural networks; forecast models; short-term load forecast



1 UVOD

Prognoziranje opterećenja u elektroenergetskom sustavu jedna je od vrlo značajnih i bitnih aktivnosti. Potreba za točnim prognoziranjem opterećenja dolazi iz prirode električne energije koja se ne može pohraniti, a koja se u novije vrijeme na tržištu počinje trenirati kao i svaki drugi proizvod. Za predviđanje opterećenja potrebna je procjena buduće potrošnje, kako prilikom planiranja proizvodnje, tako i prilikom kupovine uz uvažavanje ekonomskih i drugih kriterija.

Početna aktivnost u prognoziranju opterećenja je planiranje razvoja potrošnje električne energije. To je potrebno učiniti radi planiranja razvoja proizvodnih i prijenosnih kapaciteta. Poznavanjem tih podataka može se ići i korak dalje, sve do planiranja i razvoja svih ostalih dijelova elektroenergetskog sustava.

Osnovne veličine s kojima se susreću prognozeri, a koje se trebaju uvažiti i riješiti, su:

- prognoza potrošnje električne energije,
- prognoza vršnih (maksimalnih) snaga, kao i
- prognoza krivulje trajanja opterećenja.

U novije vrijeme za rješavanje ovih problema pojavio se novi pristup temeljen na primjeni tehnika umjetne inteligencije za simboličku analizu obrade podataka

Tim modelima obrađuje se velik broj podataka puno brže, a rezultati su točniji i precizniji nego pri korištenju klasičnih metoda, prema [1]. Različiti modeli opterećenja mogu se riješiti različitim tehnikama predviđanja opterećenja.

Temeljni cilj kratkoročnog prognoziranja opterećenja je:

- da osigura predviđanje opterećenja za funkcije planiranja temeljne proizvodnje,
- za procjenu sigurnosti djelovanja elektroenergetskog sustava i
- za povremene informacije dispečerima.

Poznato je da kratkoročno prognoziranje igra važnu ulogu u tradicionalnim monopolističkim elektroenergetskim sustavima.

Postoje dvije različite kategorije prognoziranja opterećenja, a one su:

- prognoziranje opterećenja radi planiranja elektroenergetskog sustava i
- prognoziranje opterećenja radi vođenja elektroenergetskog sustava.

1 INTRODUCTION

Load forecasting in an EPS is one of very important and crucial activities. A need for accurate load forecasts stems from the very nature of electric power which cannot be stored, but which is recently treated on the market like any other product. Load forecasting requires an assessment of future consumption, in both the planning of generation facilities and the purchasing of electricity, with economic and other criteria to be taken into consideration.

The initial activity in load forecasting consists in planning the progress of electricity consumption. This should be done as a prerequisite for planning the development of generation and transmission facilities. Knowing this information may enable us to take the next step towards the planning and developing of all the rest of the parts of the EPS.

The basic quantities encountered by the forecasters that must be heeded and solved are:

- electricity consumption forecast,
- peak (maximum) power forecast, and
- load duration curve forecast.

In addressing these problems, a new approach has emerged recently, one based on the application of artificial intelligence techniques for a symbolic analysis of data processing.

By means of these models a great number of data is processed much faster and the results are more accurate and precise than is the case with the use of classical methods, according to [1]. Various load models can be addressed by means of various load forecasting techniques.

The main goal of short-term load forecasting is to:

- ensure load forecasts for the functions of planning the basic generation,
- assess the operating safety of an electric power system, and
- provide occasional information to dispatchers.

It is well known that the short-term forecasting plays a major role in the traditional monopolistic electric power systems.

There are two different load forecasting categories:

- load forecasting for EPS planning, and
- load forecasting for EPS management.

Pri izradi modela kojim bi se kratkoročno prognoziralo opterećenje, moraju se uvažiti zahtjevi koji se pred njega postavljaju. U ovom radu istraživan je model kratkoročnog prognoziranja opterećenja, zasnovan na utjecaju vremenskih i meteoroloških faktora.

2 KRATKOROČNO PROGNOZIRANJE OPTEREĆENJA

Kratkoročno prognoziranje opterećenja poglavito dobiva sve veću važnost porastom konkurencije na tržištu električne energije. Prognoze opterećenja dobivaju značajnu ulogu u oblikovanju cijena (u budućem privatiziranom i dereguliranom tržištu), te postaju od vitalnog značenja za opskrbu potrošača [2].

Prognoziranje opterećenja je međutim vrlo težak zadatak. Prvo radi toga jer su podaci o opterećenju kompleksni i razlikuju se za različita godišnja doba. Opterećenje u danom satu nije ovisno samo o opterećenju prethodnog sata, nego i o opterećenju istog sata prethodnog dana, kao i o opterećenju istog sata pojedinog dana iz prethodnog tjedna. Drugo, budući da postoje mnoge značajne uzročne varijable koje se moraju razmotriti, potrebno je istaknuti varijable koje su povezane s vremenom.

Vremenska analiza vrlo je efikasna metoda za kreiranje matematičkog modela kojim se može riješiti široki spektar kompleksnih problema. Ti modeli koriste se za prepoznavanje ili predviđanje karakteristika fenomena predstavljenog pomoću niza promatranja. Međutim, izrada jednog preciznog modela vremenske analize koji predstavlja nelinearne procese ili procese koji imaju vrlo široka odstupanja vrlo je teška.

Umjetne neuronske mreže uspješno se koriste za rješavanje širokih odstupanja unutar razmatranih podataka kod zahtijevanih linearnih ili nelinearnih procesa. Uspješnost aplikacije umjetne neuronske mreže leži u činjenici da su te mreže pravilno trenirane i dobro konfigurirane, te omogućuju dobru aproksimaciju bilo koje mjerene vrijednosti.

Neuroni uče obrasce skrivene u podacima i čine poopćenje tih obrazaca bilo prisustvom šuma ili pri mogućem izostanku pojedinih mjerenja. Predviđanja se obavljaju na promatranim mjerenim vrijednostima s umjetnim neuronskim mrežama. Jedan primjer predviđanja problema vremenske analize koji se može riješiti s umjetnom neuronskom mrežom je predviđanje opterećenja. Precizne metode predviđanja opterećenja vode do porasta efikasnosti opskrbe kupaca električnom energijom. Nadalje, točna predviđanja mogu uštedjeti troškove opskrbljivača električnom energijom.

In preparing a model for short-term load forecasting, one must make allowance for the requirements set on the model. The present work explores a short-term load forecasting model based on the impact of weather and meteorological factors.

2 SHORT-TERM LOAD FORECASTING

Short-term load forecasting is gaining in importance with rising competition in electricity market. Load forecasts are assigned a significant pricing role (in the future privatized and deregulated market) and are becoming vital in terms of consumer supply [2].

Load forecasting, however, is not an easy job at all. First, because load data are highly complex and they differ from season to season. Load in a given hour depends not only on the load of the previous hour, but also on the load of the same hour of the day before, as well as the load of the same hour in a particular day of the previous week. Second, in view of the existence of many significant causal variables to be considered, it is necessary to single out the weather-related variables.

Weather analysis is a very efficient method for creating a mathematical model with which a broad spectrum of complex problems can be solved. These models are used for the identification or anticipation of the characteristics of a phenomenon presented through a series of observations. However, a precise weather analysis model representing nonlinear processes or processes with wide deviations is very hard to provide.

Artificial neural networks are successfully used in dealing with wide deviations within studied data when it comes to demanding linear and nonlinear processes. The success of the application of an artificial neural network lies in the fact that these networks are correctly trained and well configured and thus allow a good approximation of any measured value.

Neurons learn patterns hidden in data and generalize these patterns either through the presence of noise or the absence of some measurements. Forecasts are made on the observed measured values with artificial neural networks. An example of forecasting a weather analysis problem that can be solved by means of the artificial neural network is load forecasting. Precise load forecasting methods lead to greater efficiency in consumer electricity supply. Furthermore, accurate forecasts can save the costs of electricity suppliers.

3 OPIS MODELA NEURONSKIH MREŽA

Danas je poznato da se ljudski mozak sastoji od velikog broja živčanih stanica (neurona), koji pri obradi različitih vrsta informacija rade paralelno. Neurofiziološka istraživanja daju naslutiti da je modelu mozga najsličniji model u kojem brojni procesni elementi podatke obrađuju paralelno.

Umjetna neuronska mreža umjetna je replika ljudskog mozga kojom se nastoji simulirati postupak učenja. Analogija s pravim biološkim uzorom zapravo je dosta slaba, jer uz mnoga učinjena pojednostavljenja postoje još mnogi fenomeni živčanog sustava koji nisu modelirani umjetnim neuronskim mrežama, kao što postoje i karakteristike mreža koje se ne slažu s onima bioloških sustava.

Neuronske mreže odlično rješavaju probleme klasifikacije i predviđanja, odnosno općenito sve probleme kod kojih postoji odnos između ulaznih i izlaznih varijabli, bez obzira na visoku složenost te veze (nelinearnost).

3.1 Biološki neuron

Za razumijevanje sposobnosti mozga nužno je upoznati građu njegova sastavna dijela: neurona (živčane stanice). Četiri su osnovna dijela neurona: tijelo stanice (soma), skup dendrita (ogranaka), aksona (dugačke cjevčice koja prenosi električne signale) i niza završnih članaka. Mali razmak između završetka aksona prethodnog neurona i dendrita ili tijela sljedećeg neurona naziva se sinapsa. Slika 1 prikazuje građu neurona.

3 THE NEURAL NETWORK MODEL

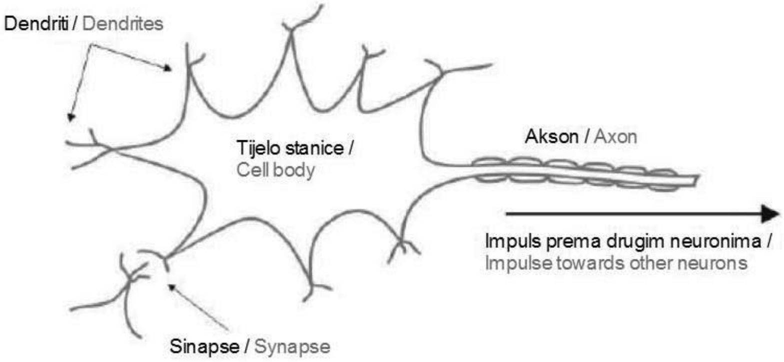
Today we know that the human brain consists of a vast number of nervous cells (neurons) which in the processing of various types of information operate in parallel. Neurophysiological investigations suggest that the model most similar to the model of the human brain is one in which numerous processing elements are handling data in parallel.

The artificial neural network is an artificial replica of the human brain with which it is attempted to simulate the learning process. Analogy with the real biological model is in fact quite weak, because with all the simplifications that have been made there are still many phenomena of the nervous system which are not modeled by the artificial neural networks, just as there are network features that do not match those of the biological systems.

The neural networks splendidly cope with the problems of classification and forecasting, generally, with all the problems in which a relationship between input and output variables is involved, irrespective of the high complexity of that link (nonlinearity).

3.1 The biological neuron

Understanding the brain's faculties requires a foreknowledge of its constituents: the neurons (nervous cells). A neuron consists of four basic parts: the cell body (soma), a set of dendrites (branches), axons (long cable-like projections conducting electrical impulses) and a series of extensions. A small junction between the ending of the axon of the preceding neuron and dendrite or the body of the next neuron is called synapse. The structure of neurons is shown in Figure 1.



Slika 1 — Građa neurona
Figure 1 — Neuron structure

Funkcionalnost biološkog neurona, prema [3] imitira McDulloch–Pitts-ov model umjetnog neurona. Model koristi sljedeću analogiju: signali su opisani numeričkim iznosom i na ulazu u neuron množe se težinskim faktorom koji opisuje jakost sinapse. Signali pomnoženi težinskim faktorima zatim se analogno sumiraju u tijelu stanice, a ako je dobiveni iznos iznad definirana praga, neuron daje izlazni signal.

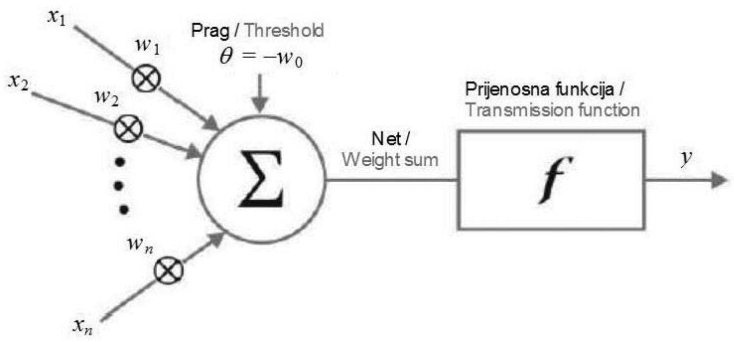
3.2 Umjetni neuron

Umjetni neuron umjesto funkcije praga može imati i neku drugu funkciju, tzv. prijenosnu funkciju ili aktivacijsku funkciju. Općeniti model umjetnog neurona prikazuje slika 2.

The functionality of the biological neuron, according to [3] is imitated by the McCulloch-Pitts neural model. The model makes use of the following analogy: the signals are described by a numerical amount and at the entrance to the neuron are multiplied by the weight factor which describes the strength of the synapse. The signals multiplied by the weight factors are then analogously summed in the cell body and if the obtained amount is above the defined threshold, the neuron gives an output signal.

3.2 Artificial neuron

The artificial neuron can have a function other than the threshold function, the so-called transmission or activation function. The general artificial neuron model is shown in Figure 2.



Slika 2 — Umjetni neuron
Figure 2 — Artificial neuron

Ulazni signali, njih ukupno n n, označavaju se sa $x_1, x_2, ..., x_n$. Težine se označavaju sa $w_1, w_2, ..., w_n$. Ulazni signali općenito su realni brojevi u intervalu [-1,1] ili [0,1]. Težinska suma net dana je sa:

Input signals, totaling nn, are denoted $x_1, x_2, ..., x_n$. The weights are denoted $w_1, w_2, ..., w_n$. Input signals, generally, are real numbers on the interval [-1,1] or [0,1]. The weight sum net is given by:

$$net = w_1x_1 + w_2x_2 + \cdots + w_nx_n - \theta \, , \tag{1}$$

ali se zbog kompaktnosti često dogovorno uzima da je vrijednost praga $\theta = -\omega_0$, te se dodaje ulazni signal x_0 s fiksiranom vrijednošću 1, pa je jednostavniji izraz:

But for the sake of compactness it is often agreed that the threshold value is $\theta = -\omega_0$, and the input signal x_0 is added with the fixed value of 1, so we get the following simplified expression:

$$net = w_0x_0 + w_1x_1 + w_2x_2 + \cdots + w_nx_n = \sum_{i=0}^{n} w_ix_i \, , \tag{2}$$

dok je za izlaz y rezultat prijenosne funkcije primijenjen na izraz (2):

whereas for the output y the result of the transmission function applied to expression (2) is:

$$y = f\left(\sum_{i=1}^{n} w_i x_i\right) = f(net)\,. \tag{3}$$

3.3 Aktivacijske funkcije

Model umjetnog neurona, prema slici 2, može se razmatrati prema ugrađenoj prijenosnoj funkciji. Izlaz iz sumatora povezuje se na ulaz aktivacijske funkcije, koja na svom izlazu producira izlaz umjetnog neurona.

Aktivacijske funkcije mogu biti linearne i nelinearne. Kod linearnih, izlaz sumatora množi se s nekim faktorom (pojačanjem) i tako dobiva izlaz neurona. Nelinearne aktivacijske funkcije mogu poprimiti različite oblike, ali se najčešće koriste: funkcije praga osjetljivosti, sigmoidalne, hiperbolične i harmoničke funkcije.

Pored mnogobrojnih prijenosnih funkcija za izradu modela kratkoročnog prognoziranja opterećenja izabrana je sigmoidalna funkcija (slika 3). Ova funkcija je odabrana budući da je derivabilna, što je bitna prednost pri postupku učenja umjetne neuronske mreže. Višeslojna neuronska mreža sa sigmoidalnom funkcijom kao prijenosnom funkcijom procesnih elemenata bit će u stanju predstaviti nelinearne odnose ulaznih i izlaznih podataka. Sigmoidalna funkcija je definirana kao:

3.3 Activation functions

Artificial neural model, shown in Figure 2, can be studied according to the installed transmission function. The output from the summator is linked to the input of the activation function which at its output produces the output of the artificial neuron.

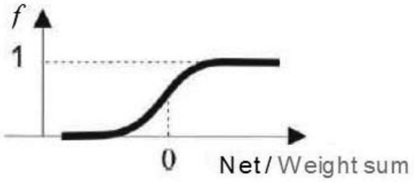
The activation functions can be linear and nonlinear. With the linear functions the summator output is multiplied with a certain factor (enhancement) and thus the neural output is obtained. The nonlinear activation functions may assume different shapes, but mostly used are: sensitivity threshold functions, sigmoidal, hyperbolic and harmonic functions.

Alongside many transmission functions for preparing short-term load forecasting models, the sigmoidal function (Figure 3) has been selected, because it is derivable, and that is a crucial advantage in the learning process of an artificial neural network. A multiple neural network with the sigmoidal function as the transmission function of processing elements will be able to present nonlinear relations of input and output data. The sigmoidal function is defined as:

$$f(net) = \frac{1}{1 + \mathrm{e}^{-a \cdot net}}\,, \tag{4}$$

gdje parametar a određuje nagib funkcije.

where parameter a defines the gradient of the function.



Slika 3 — Aktivacijska sigmoidalna funkcija
Figure 3 — Sigmoidal activation function

U slučaju da se od neuronske mreže zahtijeva rad s podacima čije vrijednosti bilo na njezinom ulazu ili izlazu nisu u uobičajenom intervalu [-1,1] najjednostavnije je rješenje provesti pred-procesiranje, odnosno post-procesiranje podataka.

If the neural network is expected to work with data the values of which are not within the usual interval [-1.1] whether at its input or its output, the simplest solution is to undertake data pre-processing and data post-processing respectively.

3.4 Učenje mreže

Prije postupka obrade podataka umjetnu neuronsku mrežu je potrebno naučiti ili trenirati. Za razliku od konvencionalnih tehnika obrade podataka gdje je postupak obrade potrebno analitički razložiti na određeni broj algoritamskih koraka, kod neuronske mreže takav algoritam ne postoji. Znanje o obradi podataka pohranjeno je implicitno u težinama veza između neurona. Te se težine postupno prilagođavaju kroz postupak učenja neuronske mreže sve do trenutka kada je izlaz iz mreže, provjeren na skupu podataka za testiranje, zadovoljavajući.

Pod postupkom učenja kod neuronskih mreža podrazumijeva se iterativan postupak predočavanja ulaznih primjera i eventualno očekivana izlaza.

Ovisno o tome da li je u postupku učenja znan izlaz iz mreže, pa se pri učenju mreže koristi uz svaki ulazni primjer ili je točan izlaz nepoznat, razlikuju se dva načina učenja:

- učenje s učiteljem – gdje se učenje mreže provodi u obliku para (ulaz, izlaz),
- učenje bez učitelja – gdje mreža uči bez poznavanja izlaza.

Skup primjera za učenje često se dijeli na tri odvojena skupa:

- skup za učenje,
- skup za testiranje,
- skup za provjeru (validaciju).

Primjeri iz skupa za učenje služe za učenje u užem smislu, tj za podešavanje težinskih faktora. Pomoću primjera iz skupa za testiranje tijekom učenja vrši se provjera rada mreže s trenutnim težinskim faktorima kako bi se postupak učenja zaustavio u trenutku degradacije performansi mreže. Umjetnu je neuronsku mrežu moguće pretrenirati, nakon određenog broja iteracija, te mreža gubi svojstvo generalizacije i postaje stručna za obradu podataka iz skupa primjera za učenje dok preostale podatke obrađuje loše. Točnost i preciznost obrade podataka moguće je na kraju provjeriti nad trećim skupom primjera, a to je skup za validaciju.

Kod učenja umjetne neuronske mreže postoji još i iteracija koja kazuje korak u algoritmu postupka za učenje u kojem se odvija podešavanje težinskih faktora. Epoha predstavlja jedan cjelokupni skup za učenje.

Pregled funkcija za provedbu treniranja iz Matlab-ovih alata, prema [4] dan je u tablici 1.

3.4 The network's learning

Prior to data processing, the artificial neural network must be taught and trained. Unlike the conventional data processing techniques where the processing procedure should be analytically broken down into a certain number of algorithmic steps, with the neural network there is no such algorithm. The knowledge about data processing is implicitly stored in the weights of interneural links. These weights are gradually adapted through the learning process of the neural network up to the moment when the network output, validated on the set of test data, is satisfactory.

Meant by the learning process when it comes to the neural networks is the iterative process of presenting input examples and an expected output, if any.

Depending on whether the network output is known in the learning process, so that in the network's learning it is used with every input example, or the exact output is unknown, there are two learning modes:

- learning with the teacher – where the network's learning is conducted in the form of a pair (input, output),
- learning without the teacher – where the network learns without knowing the output.

A set of examples for learning is often divided into three separate sets:

- learning set,
- testing set,
- validation set.

Examples from the learning set serve for leaning in the narrower sense of the word, i.e., for adjusting the weight factors. By means of the examples from the testing set the network's operation is validated with current weight factors so as to stop the learning process at the moment of the network's performance degradation. The artificial neural network can be pre-trained after a certain number of iterations and the network will lose the generalization property and will become competent for data processing from the set of learning examples, whereas for other data its processing will be poor. The accuracy and precision in data processing can be validated at the end on the third set of examples, and that is the validation set.

With the learning of the artificial neural network there is also an iteration which tells the step in the learning process algorithm in which the weight factors are being adjusted. The epoch is one whole learning set.

A survey of training functions in Matlab Toolbox, according to [4] is given in Table 1.

Tablica 1 – Prikaz funkcija treniranja iz programskog paketa Matlab
Table 1 – Training functions in Matlab Toolbox

Ime funkcije / Function name	Algoritam / Algorithm
Trainb	Skupina treniranja s težinama i postavljenim pravilima učenja / Batch training with weight and bias learning rules
Trainbfg	BFGS Newton-ov backpropagation algoritam / BFGS Newton backpropagation algorithm
Trainbr	Bayes-ova regularizacija / Bayesian regularization
Trainc	Algoritam s cikličkim slijedom prirasta treniranja težina odn. funkcija učenja / Cyclical order weight/bias training
Traincgb	Powell-Beale-ov konjugirano gradijentni backpropagation / Powell-Beale conjugate gradient backpropagation
Traincgf	Fletcher-Powell-ov konjugirano gradijentni backpropagation / Fletcher-Powell conjugate gradient backpropagation
Traincgp	Polak-Ribier-ov konjugirano gradijentni backpropagation / Polak-Ribier conjugate gradient backpropagation
Traingd	Gradijentno opadajući backpropagation / Gradient descent backpropagation
Traingdm	Gradijentno opadajući backpropagation s inercijom / Gradient descent with momentum backpropagation
Traingda	Gradijentno opadajući backpropagation s prilagodljivom brzinom učenja / Gradient descent with adaptive learning backpropagation
Traingdx	Gradijentno opadajući backpropagation s inercijom i prilagodljivom brzinom učenja / Gradient descent with momentum and adaptive learning backpropagation
Trainlm	Levenberg-Marquardt-ov backpropagation / Levenberg-Marquardt backpropagation
Trainoss	Sekantni backpropagation jediničnog koraka / One-step secant backpropagation
Trainr	Algorithm sa slučajnim slijedom prirasta treniranja težina odn. funkcija učenja / Random order incremental training with learning functions
Trainrp	Elastični backpropagation / Resilient backpropagation
Trains	Algorithm sa sekvencijskim slijedom prirasta treniranja težina odn. funkcija učenja / Sequential order incremental training with learning functions
Trainscg	Skalirani konjugirano gradijentni backpropagation / Scaled conjugate gradient backpropagation

Ove funkcije korištene su za treniranje mreže, a kao najbolje za model kratkoročnog prognoziranja krivulja opterećenja pokazale su se: traincgp, traincgf i trainscg. One su imale najbolji odziv prilikom postupka učenja i bile su najsličnije izvornim podacima unatoč velikim nesigurnostima ulaznih podataka, pogotovo podataka o temperaturama. Stoga je odabir ovih funkcija treniranja predstavljao dobar izbor za učenje mreže, kao i za njihovu implementaciju u modelu.

4 PRIMJENA UMJETNE NEURONSKE MREŽE NA KRATKOROČNO PROGNOZIRANJE OPTEREĆENJA

Ideja za korištenje modela umjetne neuronske mreže u prognoziranju opterećenja dolazi od zamisli da je buduće opterećenje ovisno o prošlim opterećenjima i utjecaju vanjskih faktora (npr.

These functions are used for network training. For the short-term forecasting model traincgp, traincgf and trainscg have proved to be the most effective. They had the best response during the learning process and were closest to the original data in spite of major uncertainties of input data, especially those on temperatures. That is why the selection of these training functions was a good choice for network learning as well as for their implementation in the model.

4 APPLICATION OF THE ARTIFICIAL NEURAL NETWORKS TO SHORT-TERM LOAD FORECASTING

The idea of using the artificial neural network model in load forecasting comes from the notion that the future load depends on the past loads and the influence of external factors (notably, temperatu-

temperature, vlažnosti, i dr.), te je potrebna mreža za aproksimaciju te ovisnosti. Ulazi u mrežu trebaju sadržavati vrijednosti temperature, prema [5] i vrijednosti opterećenja prethodnih dana, a za izlaz trebaju se dobiti vrijednost opterećenja (npr. vrijednosti opterećenja pojedinih dana ili vrijednost opterećenja pojedinih godišnjih doba).

Radeći na izradi takvog modela opterećenje se može prepoznati kao nelinearni sustav kojeg je potrebno riješiti. Prilikom određivanja strukture modela potrebno je obuhvatiti ulazne varijable i odrediti mrežnu strukturu. Ovdje se moraju uzeti u obzir brze promjene u karakteristikama ponašanja opterećenja, te mogućnosti prepoznavanja obrasca ponašanja opterećenja i temperatura. Ti zahtjevi i ulazi u mrežu potrebni su za prepoznavanje uvjeta koje je potrebno provesti za treniranje mreže, te pronalazak prikladnog algoritma učenja prilagođenog podacima za treniranje mreže.

Model koji je sposoban riješiti postavljene zahtjeve bio bi model višeslojne unaprjedne neuronske mreže, koja je definirana sa tri sloja: ulaznim, skrivenim i izlaznim.

5 IZRADA POČETNOG MODELA

5.1 Arhitektura umjetne neuronske mreže

Kod dizajniranja umjetne neuronske mreže za kratkoročno prognoziranje opterećenja, prema [6] ulazni parametri definirani su kako slijedi:

re, humidity, etc.), so a network is required for the approximation of this dependence. Network inputs should contain temperature values, according to [5] and load values of the preceding days, whereas for the output the load values (e.g., load values of particular days or load values of particular periods of the year) are required.

While working on such a model, load can be perceived as a nonlinear system requiring a solution. In defining the structure of the model it is necessary to include input variables and define the network's structure. What must be taken here into account are fast changes in the load behavior characteristics and the possibility of identifying the behavioral pattern of loads and temperatures. These requirements and network inputs are needed for identifying the network training conditions to be created and for finding a suitable learning algorithm adapted to network training data.

A model capable of meeting the set requirements would be one of multilayer feedforward neural network defined by three layers: input, hidden and output layers.

5 MAKING THE INITIAL MODEL

5.1 Architecture of the artificial neural network

In designing the artificial neural network for short-term load forecasting, according to [6] the input parameters are defined as follows:

$$L = L_\mathrm{n} + L_\omega + L_\mathrm{s} + L_\mathrm{r} \ , \qquad (5)$$

gdje je:

L – ukupno opterećenje sustava,
L_n – predstavlja normalni dio opterećenja koje je određeno standardiziranom krivuljom opterećenja za svaki tip dana u bilo kojem dijelu godine,
L_ω – predstavlja meteorološki promjenjivi dio opterećenja, koji je u čvrstoj povezanosti s godišnjim dobom unutar godine,
L_s – predstavlja posebne događaje (manifestacije) koji su slučajni, neuobičajeni sa znatnim odstupanjem od tipičnog ponašanja krivulje opterećenja,
L_r – je potpuno nasumični uvjet koji predstavlja bijeli šum.

Za ulaze modela kratkoročnog prognoziranja op-

where:

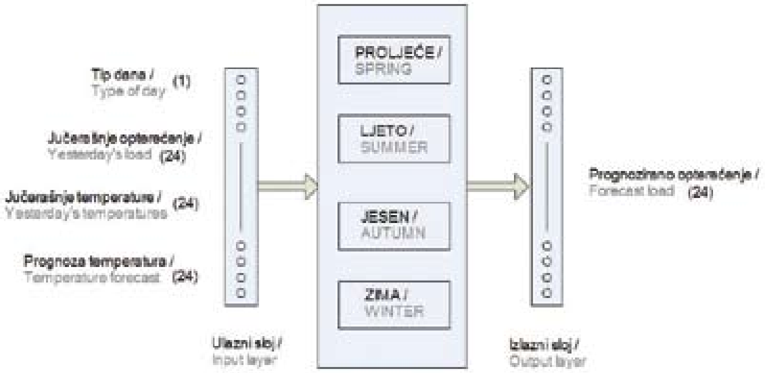
L – total system load,
L_n – normal part of the load defined by the standardized load curve for every type of day in any part of the year,
L_ω – meteorologically variable part of the load firmly linked to the season within a year,
L_s – special events (manifestations) which are random, unusual, with considerable deviations from the typical shape of the load curve,
L_r – a complete random condition representing white noise.

For the inputs of the short-term load forecasting model two parameters were used: the loads of previous days and temperatures. Load forecasting for special days in the year was not carried out, terećenja koristila su se dva parametra: opterećenja prethodnih dana i temperature. Prognoziranje opterećenja za posebne dane u godini nije provedeno, već su svi dani obuhvaćeni jednim sezonskim modelom. Ti dani ne moraju biti samo posebni dani u godini, već oni mogu obuhvaćati i pojedine kvarove u mreži ili remonte u trafostanicama. Za njihovo prognoziranje bilo bi potrebno izraditi zaseban model. Blok dijagram za predloženu arhitekturu umjetne neuronske mreže prikazan je na slici 4. U ulaznom sloju definirano je 73 neurona. Prvi neuron koristi se za unos oznake dana u tjednu koji se prognozira. Dani u tjednu raspoređeni su prema sljedećem kriteriju:

- radnim danima (ponedjeljak, utorak, ... , petak) dodijeljene su vrijednosti 0,1
- subotama su dodijeljene vrijednosti 0,5, a
- nedjeljama su dodijeljene vrijednosti 1.

instead all the days were covered with a single seasonal model. These days do not need to be only the special days in the year, they can also include particular defects in the network or repair works in the substations. For their forecasting it would be necessary to make a separate model. A block diagram for the proposed architecture in shown in Figure 4. In the input layer 73 neurons are defined. The first neuron is used to enter the marker of the day in the week being forecast. The days in the week are arranged according to the following criterion:

- workdays (Monday, Tuesday, ... , Friday) are assigned values 0,1
- Saturdays are assigned values 0,5, and
- Sundays are assigned values 1.



Slika 4 — Predložena arhitektura umjetne neuronske mreže za prognoziranje opterećenja
Figure 4 — Proposed architecture the artificial neural network for load forecasting

Ulaz sljedećih 24 neurona predstavlja dnevno satno opterećenje prethodnog dana. Ovdje se mogu i unijeti podaci o opterećenju cijelog prethodnog tjedna. Time se drastično povećava mreža i gubi točnost.

Sljedećih 48 neurona koristi se za uvid u efekt temperature. Prva 24 neurona koriste se za dnevne temperature prethodnog dana, a sljedeća 24 neurona za prognozu temperature prognoziranog dana. U skrivenom sloju koriste se četiri sezonske mreže. Izlazni sloj svih sezonskih mreža sadrži 24 neurona. Ti neuroni predstavljaju 24 sata u danu za koje se vrši prognoziranje.

U ovom radu razrađena su dva modela za kratkoročno prognoziranje opterećenja, a to su:

- model sezonske umjetne neuronske mreže i
- model višestrukog prognoziranja dana.

The input of the next 24 neurons represents the daily hourly load of the previous day. Here one can also enter load data of the whole previous week. Thereby the network is drastically expanded and loses in accuracy.

The next 48 neurons are used for an insight into the temperature effect. The first 24 neurons are used for daily temperatures of the previous day, and the next 24 neurons for forecasting the temperature of the forecast day. In the hidden layer four seasonal networks are used. The output layer of all seasonal networks contains 24 neurons. These neurons represent 24 hours in the day in which forecasting is done.

The present work elaborates on two short-term load forecasting models, viz.:

- seasonal artificial neural network model, and
- multiple day forecasting model.

5.2 Sezonska umjetna neuronska mreža

Za izradu ovog modela uzimaju se u obzir četiri modela umjetne neuronske mreže za:

— proljeće,
— ljeto,
— jesen i
— zimu.

Svako pojedino godišnje doba predstavlja se sa svojim modelom, koji su neovisni jedan o drugom u prognoziraju opterećenja. Pri procesu treniranja svakoj mreži dostupni su podaci opterećenja pojedinog godišnjeg doba, a za treniranje uzeto je u obzir dvogodišnje razdoblje.

Četiri sezonske mreže imaju iste arhitekture, koje su unaprjedne neuronske mreže s tri sloja. To je prikazano na slici 5, gdje je za ulazni sloj korišteno 73 neurona, za skriveni sloj 90 neurona, a za izlazni sloj 24 neurona.

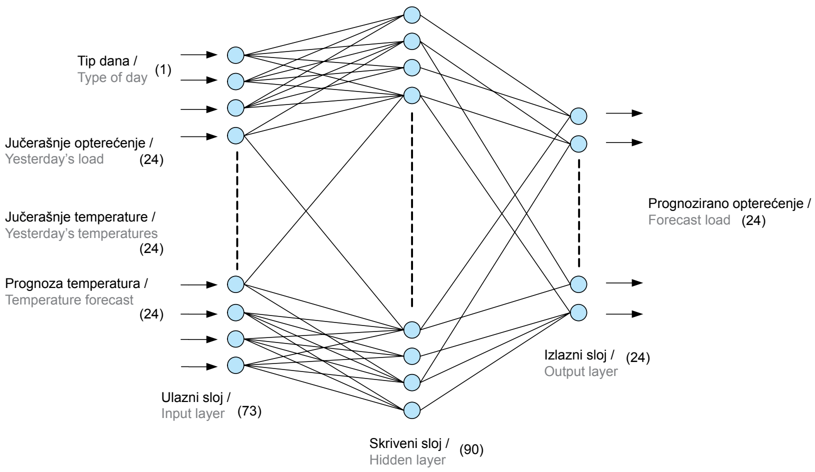
5.2 Seasonal artificial neural network

In designing this model, four artificial neural network models are taken into account for:

— spring,
— summer,
— autumn, and
— winter.

Each season is represented by its own model and each model is independent of the other in load forecasting. In the training process each network has access to the load data of a particular season, and for training a two-year period is taken into consideration.

Four seasonal networks share the same architecture which are three-layered feedforwarding networks. This is shown in Figure 5, where for the input layer 73 neurons are used, for the hidden layer 90 neurons, and for the output layer 24 neurons.



Slika 5 — Sezonska mrežna arhitektura za prognoziranje opterećenja
Figure 5 — Seasonal network architecture for load forecasting

Broj neurona u ulaznom i izlaznom sloju je fiksan i temelji se na izboru ulaznih i izlaznih podataka. Broj neurona u skrivenom sloju određen je prema ranije predloženim pravilima, a treniranje mreže vršilo se postupno počevši s manjim brojem neurona, pa sve do konačnog određivanja broja neurona. Mreža je trenirana s raznim brojem neurona skrivenog sloja, a pokazalo se da u skrivenom sloju ne smije biti manje od 50 neurona niti više od 150 neurona, jer se drastično povećava pogreška. Shodno tome, došlo se do odgovarajućeg broja neurona u skrivenom sloju za kojeg je odlučeno da bude 90 neurona, a koji se temelji na vremenu i rezultatima treniranja.

The number of neurons in the input and output layers is fixed and based on the choice of input and output data. The number of neurons in the hidden layer is defined by the previously proposed rules. Network training was carried out gradually beginning with a smaller number of neurons until the number of neurons was finally defined. The network was trained with a varying number of neurons in the hidden layer. It turned out that in the hidden layer there must be no less than 50 neurons and not more than 150 neurons, otherwise the error is rising dramatically. Thus a proper number of neurons in the hidden layer had to be arrived at, decided to be 90, a number based on the timing and results of training.

5.3 Višestruko prognoziranje dana

Pored navedenog modela sezonske umjetne neuronske mreže izrađen je i model višestrukog prognoziranja opterećenja za nekoliko dana unaprijed. Ovaj model može se predočiti sa sljedećom strategijom:

Prognoziranje opterećenja za dan $d+1$ izvodi se s opterećenjem prethodnog dana (d) i s temperaturom prethodnog dana (temperatura (d))

Ovo se izvodi dok je dostupna prognoza temperature dana ($d+k$), a taj se postupak može ponavljati do ($d+k$) puta.

U ovom modelu postoji mogućnost za dvije varijante:

- varijanta 1 – gdje se u mrežu vraćaju oni podaci koji su stvarno izmjereni i koji su referenca za ono što bismo htjeli dobiti kao stvarni cilj (engl. target) simulacije mreže,
- varijanta 2 – gdje se u mrežu vraćaju podaci koji su simulirani s mrežom, te služe za predikciju budućih ponašanja modela.

Ilustracija ovog modela dana je na slici 6.

5.3 Multiple day forecasting

Apart from the artificial neural network model, a multiple load forecasting model for several days in advance has been made. This model can be presented with the following strategy:

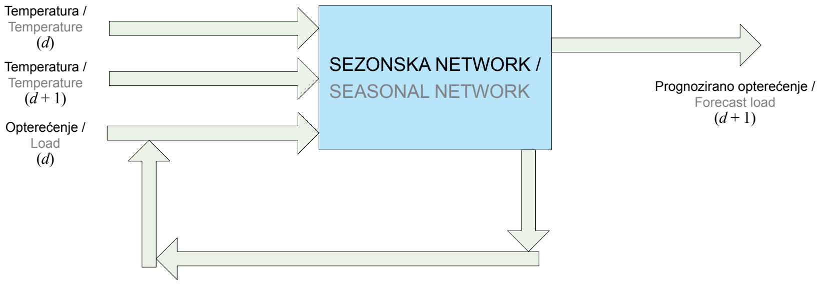
Load forecasting for day $d+1$ is performed with the load of the previous day (d) and with the temperature of the previous day (temperature (d))

This is done while the day temperature forecast is accessible ($d+k$), and that procedure can be repeated up to ($d+k$) times.

This model can accommodate two variants:

- Variant 1 – where those data return to the network which have been actually measured and which serve as reference for what we would like to get as a real target of the network simulation,
- Variant 2 – where those data return to the network which have been simulated with the network and serve for predicting the model's future behavior.

This model is illustrated in Figure 6.



Slika 6 — Višestruko prognoziranje dana
Figure 6 — Multiple day forecasting

Premda se može prognozirati i za više od sedam dana unaprijed, uglavnom se ne preporuča zbog kumulativnih pogrešaka. Budući da će svako prognoziranje imati pogrešku koja je povezana sa stvarnim opterećenjem, prognoziranje opterećenja za šire vremensko razdoblje imat će zajedničke pogreške, koje za duže vrijeme čine prognoziranje neprecizno. Sljedeći razlog zašto se ne prognozira duže od sedam dana je raspoloživost prognoze temperatura. Satnu prognozu temperature za više od sedam dana rijetko se čini u meteorološkim stanicama. Čak i kad su podaci i dostupni, prognoza neće biti vjerodostojna.

While it is possible to make forecasts even for more than seven days in advance, that is not recommended due to cumulative errors. As any forecasting will have an error linked to the real load, load forecasting for a longer period of time will have common errors which make longer-term forecasting imprecise. Another reason why forecasts are not made for a period of time longer than seven days is the availability of temperature forecasts. An hourly temperature forecast for more than seven days is rarely made at weather stations. Even if data are available, such a forecast will lack credibility.

5.4 Kriterij zaustavljanja procesa treniranja

Kriterij zaustavljanja procesa treniranja zasniva se na pogrešci dobivenoj od umjetne neuronske mreže. Za određivanje pogreške koristi se:

- apsolutna postotna pogreška i
- srednja apsolutna postotna pogreška,

koje su definirane kao:

5.4 Criterion of stopping the training process

The criterion of stopping the training process is based on an error received from the artificial neural network. Used for error definition are:

- absolute percentage error, and
- mean absolute percentage error,

defined as:

$$\left|APE\right| = \frac{\left|L_{\mathrm{f}} - L_{\mathrm{a}}\right|}{L_{\mathrm{a}}} \times 100\ \% \quad , \tag{6}$$

$$\overline{MAPE} = \frac{1}{N_{\mathrm{h}}} \sum_{N_{\mathrm{h}}} APE \ , \tag{7}$$

gdje je:

$\left|APE\right|$ – apsolutna postotna pogreška,
L_{f} – prognozirano opterećenje,
L_{a} – stvarno opterećenje,
$\overline{MAPE}$ – srednja apsolutna postotna pogreška,
N_{h} – broj sati u periodu prognoziranja.

Svaki model trenira se sa svojim vlastitim podešenjem treniranja za određenu točnost, koja se zadaje. Nakon maksimalnog broja epoha koji model može dostići, model je treniran i dobivaju se rezultati treniranja. Nakon toga ubacuju se podaci za testiranje te se dobivaju simulirane vrijednosti mreže, na osnovi realnih mjerenih vrijednosti.

Kada se usporede simulirane vrijednosti mreže nakon testiranja sa stvarno izmjerenim vrijednostima mjerenja na sabirnicama može se izračunati *APE* i *MAPE*. Svaki model postiže svoju točnost. Prihvatljiva točnost modela kreće se oko 5 %.

Postignuta točnost nije jednaka za sve modele, a razlozi mogu biti razni. Veličina vektora treniranja, odabrana funkcija treniranja, nadalje razlog može biti razlika temperatura u svakom modelu. Veća razlika u temperaturama može otežati raspoznavanje strukture umjetne neuronske mreže. Jednako tako na točnost utječu i posebni dani, kao što su vjerski ili državni blagdani i dr.

where:

$\left|APE\right|$ – absolute percentage error,
L_{f} – forecast load,
L_{a} – real load,
$\overline{MAPE}$ – mean absolute percentage error,
N_{h} – number of hours in the forecasting period.

Each model is trained with its own training adjustment for a certain given accuracy. After a maximum number of epochs that a model can reach, the model is trained and the training results are obtained. Then the test data are entered and the network's simulated values are obtained, based on really measured values.

When the network's simulated values are compared after testing with the really measured values on busbars *APE* and *MAPE* can be computed. Each model attains its level of accuracy. The acceptable accuracy of a model varies at about 5 %.

The attained accuracy is not the same for all models, and the reasons can be multifarious, such as the size of the training vector, the selected training function, or a temperature difference in any model. A greater temperature difference may adversely affect the discrimination of the structure of the artificial neural network. Likewise, accuracy is influenced by special days, such as religious or national holidays, etc.

6 MODELI KRATKOROČNOG PROGNOZIRANJA OPTEREĆENJA

6.1 Model sezonske mreže – jeseni

Za sezonsku mrežu jeseni izračunata vrijednost srednje apsolutne postotne pogreške (*MAPE*) iznosi: 3,64 %.

Na slikama 7 i 8 prikazana je krivulja opterećenja jednog slučajno odabranog dana srijede 26. listopada 2005. godine, kao i vrijednost učenja mreže istog dana. Učenje mreže provedeno je na cijelom skupu podataka.
Učenje mreže s pokazateljima točnosti treniranja, testa i validacije prikazuje slika 9.

Pogreške cijelog skupa podataka, cijelog razdoblja jeseni, prikazuje slika 10, a pogreška učenja odabranog dana, srijede 26. listopada 2005., označeno je crvenom bojom.

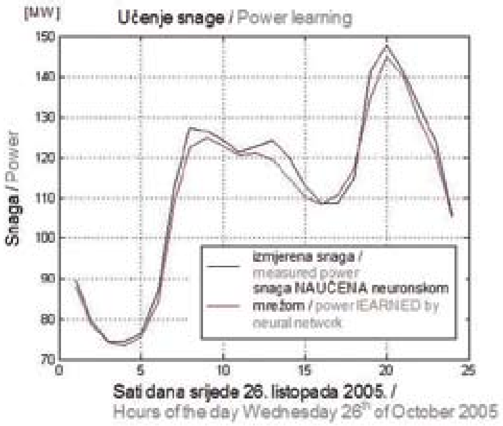
6 SHORT-TERM LOAD FORECASTING MODELS

6.1 Seasonal network model – autumn

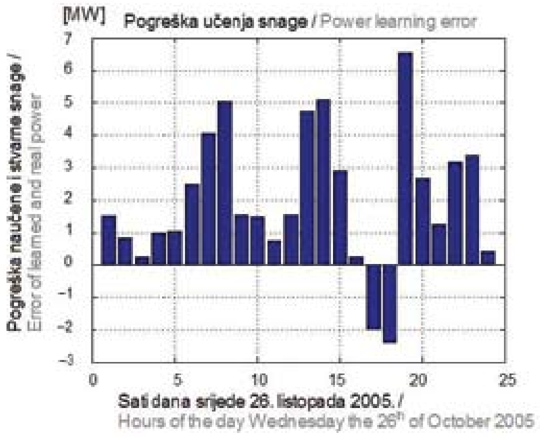
For the autumn season network the computed value of the mean absolute percentage error (*MAPE*) amounts to: 3,64 %.

Figures 7 and 8 show the load curve of a randomly selected day of Wednesday the 26th of October 2005, as well as the value of network learning of the same day. Network learning has been conducted on the whole set of data.
Network learning with training, test and validation accuracy indices are shown in Figure 9.

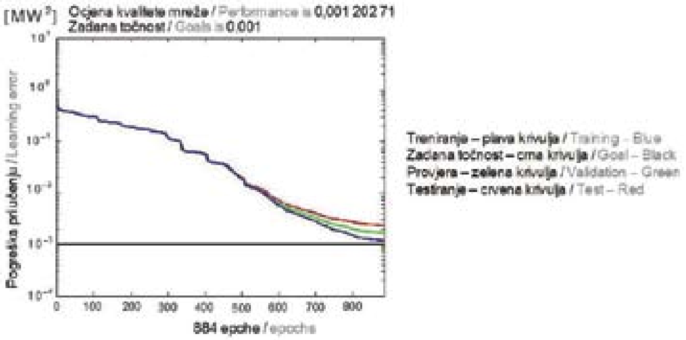
The errors of the whole set of data, the whole autumn season, are shown in Figure 10, and the learning error of the selected day, Wednesday 26th of October 2005 is marked red.



Slika 7 — Prikaz izmjerene vrijednosti krivulje opterećenja i vrijednosti dobivene učenjem mreže
Figure 7 — The measured value of the load curve and the values obtained by network learning

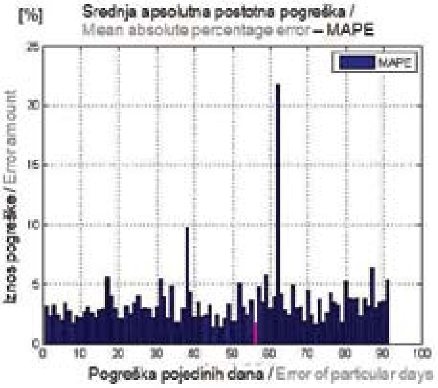


Slika 8 — Pogreške vrijednosti mjerenog opterećenja i opterećenja naučenog neuronskom mrežom za srijedu, 26. listopada 2005. godine
Figure 8 — Errors of the values of the measured load and the load learned by neural network for Wednesday the 26th of October 2005



Slika 9 — Prikaz treniranja sezonske mreže jeseni, saprikazom postignute točnosti treniranja, testa i validacije

Figure 9 — Training of the autumn season network and the attained training, test and validation accuracy

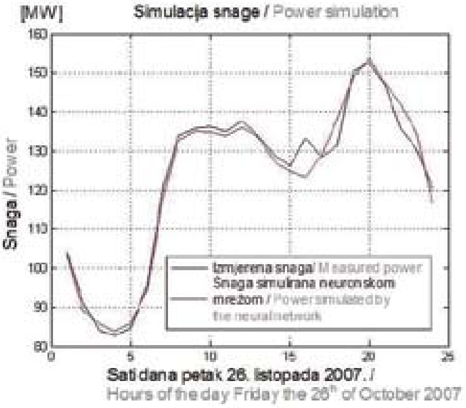


Slika 10 — Prikaz treniranja sezonske mreže jesen, s prikazom pogrešaka srijede, 26. listopada 2005. godine (crveno), kao i svih ostalih dana

Figure 10 — Training of the autumn season network and the errors of Wednesday the 26th of October (red) and all other days

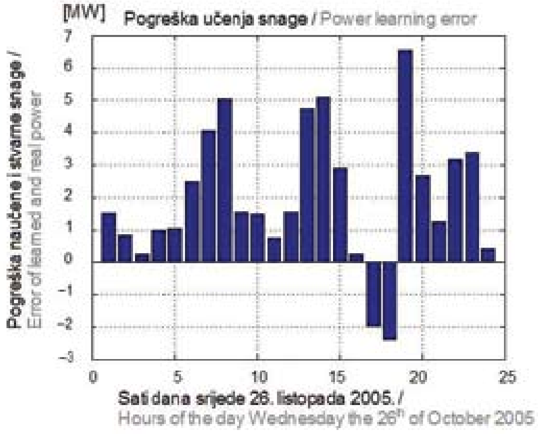
Prognozu opterećenja za 2007. godinu po završetku procesa testiranja za isti datum, 26. listopada prikazuje slika 11, gdje se uočava prognozirano opterećenje, te uspoređuje s izmjerenom vrijednošću. Slika 12. prikazuje pogreške simuliranog i mjerenog opterećenja za promatrani dan, petak 26. listopada 2007.

The load forecast for the year 2007 upon completion of the testing process for the same date, the 26th of October, is shown in Figure 11, where the forecast load is detected and compared with the measured value. Figure 12 shows the errors of simulated and measured loads for the observed day, Friday the 26th of October 2007.



Slika 11 — Prognoza opterećenja po završetku procesa testiranja za dan petak 26. listopada, te usporedba s izmjerenom vrijednošću

Figure 11 — Load forecast upon completion of the testing process for the day Friday the 26th of October and a comparison with the measured value



Slika 12 — Pogreške simuliranog i mjerenog opterećenja za promatrani dan
Figure 12 — Errors of simulated and measured loads for the observed day

Pogreške svih sezonskih mreža su u granicama do 5 %, jedino za neke pojedine dane pogreške odstupaju više od 5 %. Kada se proanaliziraju koji su to dani dobivaju se neradni dani u godini koji su vjerski ili državni praznici, kao primjerice: 1. siječnja (Nova godina), Uskrs, 1. svibanj (Praznik rada), 15. kolovoza (Velika Gospa), 1. studeni (Svi sveti), 25. i 26. prosinca (Božić), i neki drugi. Te dane potrebno je ili posebno prognozirati ili ih zanemariti, te praviti posebne prognoze opterećenja samo za njih. U sezonskim modelima korištena funkcija treniranja je logsig, gdje su podaci normirani u vrijednosti [0, 1].

6.2 Model višestrukog prognoziranja

Ovaj model, za treniranje, koristi jednogodišnje podatke – cjelokupnu 2006. godinu. Jednako tako i za provjeru skupa – za testiranje koriste se jednogodišnji podaci za 2007. godinu.

Višestruko prognoziranje provedeno je za dvije varijante:

- s povratom stvarno izmjerenih podataka i
- s povratom simuliranih podataka.

Promatrana su četiri godišnja doba u kojima se vršilo prognoziranje, te su dobivene pogreške prognoziranja na osnovi cijelog skupa podataka (za svaku sezonu – oko 90 dana).

U modelima za višestruko prognoziranje dana korištena funkcija treniranja je tansig, gdje su podaci normirani u vrijednosti [-1, 1].

Temperatura u ovom modelu bila je određivana aproksimativno, budući da nisu bile poznate prognozirane vrijednosti temperatura za svaki sat. S poznavanjem podataka o vrijednostima temperatura svakog sata povećala bi se točnost modela.

The errors of all seasonal networks are within 5 % margin, only for some days they exceed 5 %. When analyzed which days they are, it turns out that they are rest days, specifically the religious and national holidays, for example: January 1 (New Year), Easter Day, May 1 (May Day), August 15 (Assumption of the Virgin Mary), November 1 (All Saints' Day), December 25 and 26 (Christmas), and other. These days should be either separately forecast or ignored, or separate load forecast should be made only for them. The training function used in the seasonal models was logsig, where data are standardized in value [0, 1].

6.2 Multiple forecasting model

This training model is using one-year data – the whole year 2006. Likewise, for set validation – for testing, one-year data of 2007 are used.

Multiple forecasting has been carried out for two variants:

- with return of really measured data, and
- with return of simulated data.

Four periods of the year were observed in which forecasts were made, and forecast errors were obtained on the basis of the whole set of data (for each season – about 90 days).

In the models for multiple day forecasting the used training function was tansig, where data are standardized in value [-1, 1].

Temperature in this model was defined approximately, because the forecast temperature values were not known for every hour. The knowledge of data on temperature values of every hour would enhance the accuracy of the model. The accuracy of this model stands at about 5 %, so it can be

Točnost ovog modela kreće se oko 5 %, te se može reći da model zadovoljava. U literaturi se tolerira točnost do 5 %.

Prikaz pojedinih modela u ovisnosti o promatranom razdoblju, za razdoblje jeseni, predočen je na slikama 13 i 14.

Na slici 13 dan je prikaz pogreški višestrukog prognoziranja s povratom izmjerenih podataka za razdoblje jeseni.

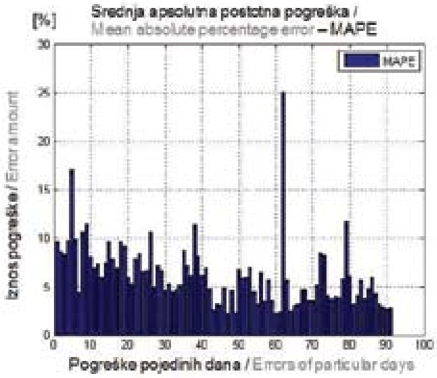
Na slici 14 dan je prikaz višestrukog prognoziranja s povratom simuliranih vrijednosti podataka za razdoblje jeseni.

described as satisfactory. In literature a margin of up to 5 % is tolerated.

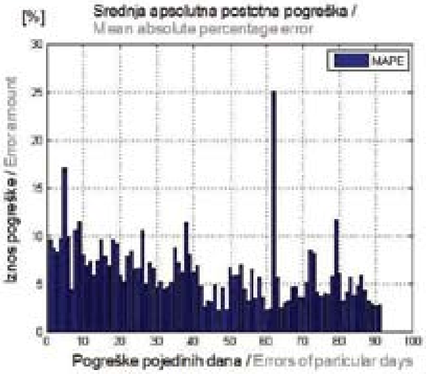
Figures 13 and 14 show individual models in dependence on the observed period for the autumn season.

Figure 13 shows errors of multiple forecasting with return of measured data for the autumn season.

Figure 14 shows multiple forecasting with return of simulated values of autumn data.



Slika 13 — Prikaz pogreški višestrukog prognoziranja s povratom izmjerenih podataka za razdoblje jeseni
Figure 13 — Errors of multiple forecasting with return of measured data for the autumn season



Slika 14 — Prikaz pogreški višestrukog prognoziranja s povratom simuliranih vrijednosti podataka za razdoblje jeseni
Figure 14 — Errors of multiple forecasting with return of simulated values of autumn data

7 ZAKLJUČAK

U ovom radu razmatrana je izrada modela za kratkoročno prognoziranje opterećenja primjenom umjetne neuronske mreže, kao i njegova šira primjena i implementacija.

Korišteni model prognozira opterećenje za jedno distribucijsko područje napajanja na sabirnicama

7 CONCLUSION

This work examines the way of making a short-term load forecasting model by using the artificial neural network, as well as its wide application and implementation.

The model is used for load forecasting for a distribution area supplied over $110 / x$ kV busbars,

$110 / x$ kV, koje je u ovom radu primijenjeno na HEP ODS Elektroslavoniju Osijek.

Model se može aplicirati i za različita druga distribucijska područja, te na širi dio mreže s drugim naponskim razinama, sve do praćenja cjelokupnog elektroenergetskog sustava. S drugim parametrima modela i poznatim ulaznim mjernim podacima moguće je kombinirati modele kratkoročnog prognoziranja opterećenja radi planiranja, održavanja itd.

Obrađen je model za jedan sustav sabirnica, ali se na ovaj način može razmatrati i više istodobnih sustava koji se mogu sinkronizirati i istodobno razmatrati.

Model se može nadopunjavati, a za šire potrebe i razdvojiti s mogućnosti razmatranja pojedinih kategorija potrošača: industrije, kućanstva ili poslovnih subjekata, te mu se može i povećati točnost s aktualnim podacima o satnim temperaturama. Važno je za napomenuti da se eliminacijom loših podataka može povećati točnost modela, kao što su smetnje prilikom kvarova, te svakako razdvajanjem prazničnih dana od radnih dana.

Implementacija oba modela omogućuje kratkoročno prognoziranje opterećenja u budućim tržišnim uvjetima kojima se osigurava:

- planiranje proizvodnje,
- sigurnost elektroenergetskog sustava,
- osiguranje rezervne proizvodnje u elektroenergetskom sustavu,
- osiguranje informacija za dispečere, te
- funkcioniranje tržišta.

Uštede primjenom ovog modela mogu biti jako velike. Povećanje točnosti predviđanja potrošnje direktno utječe na optimiranje tokova snaga, rezultat čega mogu biti manji troškovi djelatne snage. Sa smanjenjem pogreške prognoziranja opterećenja u iznosu od 1 % smanjenje djelatnih troškova može biti znatno. Radi toga interesantna je daljnja nadogradnja modela, a njegova točnost može se poboljšati nastavkom praćenja svih relevantnih podataka, te njihovim uvrštenjem u već postojeće modele.

applied in this work to HEP ODS Elektroslavonija Osijek.

The model is also applicable to other distribution areas and a wide part of the network with other voltage levels up to the point of monitoring the whole electric power system. With other parameters of the model and known input measuring data it is possible to combine the short-term load forecasting models for planning, maintenance and other purposes.

The model has been prepared for one system of busbars, but in this way a number of simultaneous systems can be studied that can be synchronized and simultaneously reviewed.

The model can be supplemented, as well as separated into parts for wider needs with a possibility of analyzing particular consumer categories: industries, households or businesses, and its accuracy can be improved by means of topical data on hourly temperatures. It is important to note that the accuracy of the model can be enhanced by eliminating bad data, such as disturbances in the case of defects, and by separating holidays from working days.

The implementation of both models allows short-term load forecasting in future market conditions to ensure:

- production planning,
- EPS security
- stand-by power generation in the EPS,
- information for dispatchers, and
- a functioning market.

The application of the model may result in huge savings. Improved prediction accuracy has a direct effect on the optimization of power flows, the result of which may be lower active power costs. A reduced load forecasting error of just 1 % can result in major reductions in active costs. For that reason further upgrade of the model is certainly of interest. Its accuracy can be improved by continued monitoring of all relevant data and its incorporation into the existing models.

LITERATURA / REFERENCES

[1] HIPPERT, H.S., PEDREIRA, C.E., SOUZA, R.C., Neural Networks for Short-Term Load Forecasting: A Review and Evaluation, IEEE Trans. Power System, Vol. 16, No. 1, 2001

[2] SHAHIDEHPOUR, M., YAMIN, H., LI, Z., Market operations in Electric power systems- Forecasting, Scheduling, and Risk Management, Wiley Interscience, A John Wiley & Sons, Inc., Publication, New York, 2002

[3] NOVAKOVIĆ, B., Umjetne neuronske mreže, Sveučilište u Zagrebu, Fakultet strojarstva i brodogradnje, Zagreb, 1998.

[4] DEMUTH, H., Neural Network Toolbox (For Use with MATLAB), The MathWorks, 1997

[5] http://radar.dhz.hr/~hep/prognoze.php?id=meteogram&param

[6] FEINBERG, E.A., GENETHLIOU. D., Load Forecasting: Applied Mathematics for Restructured Electric Power Systems: Optimization, Control, and Computational Intelligence, Springer USA, 2006

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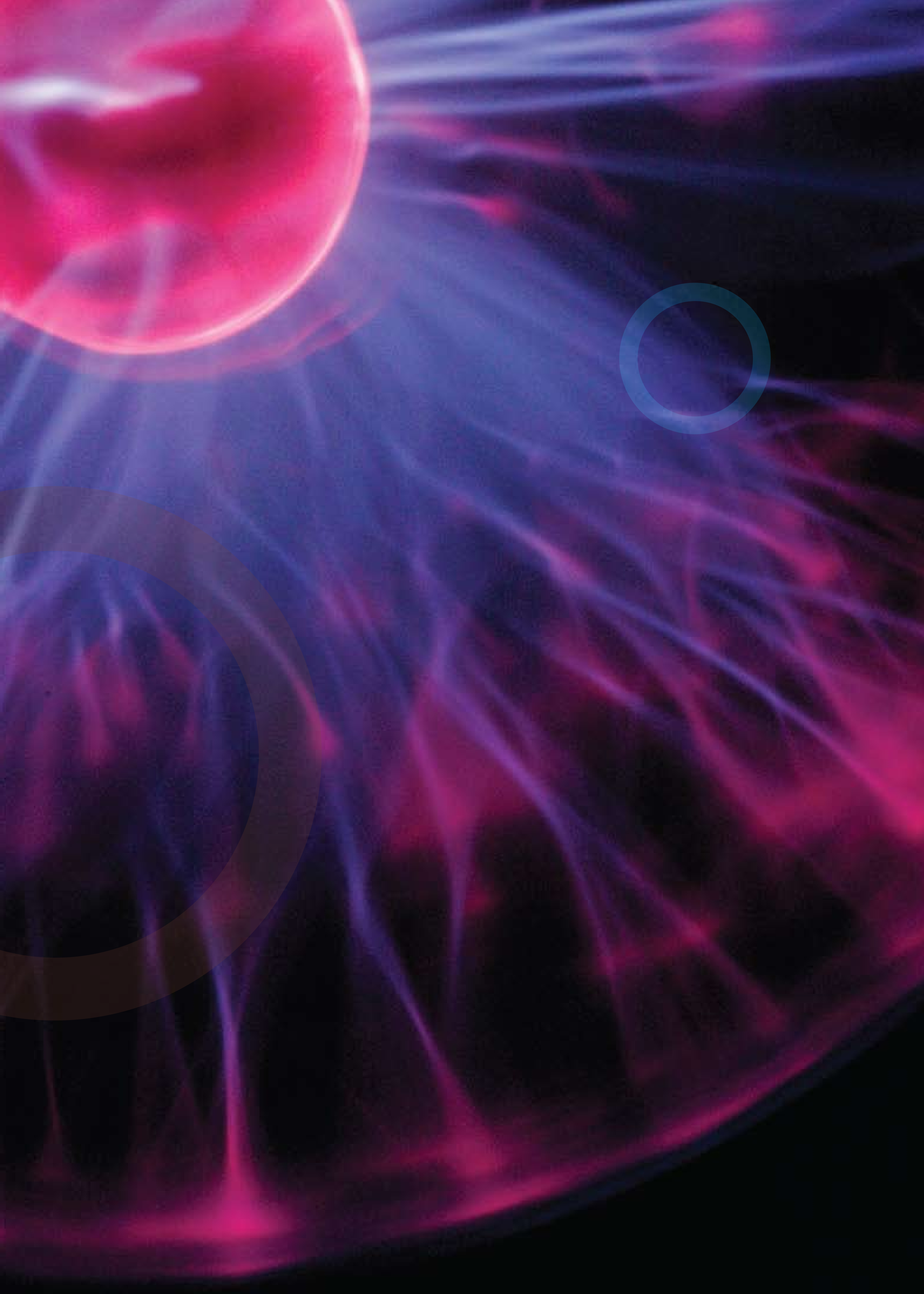
PRORAČUN KVAZISTATIČKOG ELEKTROMAGNETSKOG POLJA SLOŽENIH ELEKTROENERGETSKIH OBJEKATA

COMPUTATION OF QUASISTATIC ELECTROMAGNETIC FIELDS OF COMPLEX ELECTRIC POWER FACILITIES

Bojan Trkulja – Željko Štih, Zagreb, Hrvatska

Točan proračun niskofrekvencijskog kvazistatičkog elektromagnetskog polja značajan je za projektiranje naprava za prijenos i pretvorbu električne energije. U okviru ovog rada razrađena je teorijska podloga proračuna pomoću integralnih jednadžbi. Postupci rješavanja tih jednadžbi definirani su primjenom metode momenata i metode usklađivanja u točkama. Nepoznata raspodjela gustoće funkcije izvora na tankožičnim elementima je približena polinomima trećeg stupnja. Na pravokutnim plohama približenje nepoznate funkcije izvora realizirano je bilinearnim elementima. Razvijen je program za paralelni proračun elektromagnetskog polja temeljen na opisanoj metodi.
Accurate computation of low-frequency quasistatic electromagnetic fields is important in the design of electricity transmission and conversion devices. This work presents the theoretical groundwork of a computation using integral equations. The procedures for solving these equations are defined by applying the method of moments and the point matching method. The unknown distribution of the source function density on the thin-wire elements is approximated by the third degree polynomials. On rectangular planes the approximation of an unknown source function is achieved by means of bilinear elements. A program has been developed for the parallel electromagnetic field computation based on the described method.

Ključne riječi: integralne jednadžbe; metoda momenata; proračun elektromagnetskog polja
Keywords: integral equations; method of moments; electromagnetic field computation



1 UVOD

Elektromagnetska polja industrijske frekvencije tema su brojnih radova i istraživanja u svijetu i kod nas [1], [2], [3] i [4]. Proračun elektromagnetskih polja značajan je za projektiranje naprava za prijenos i pretvorbu električne energije. Nepovoljni utjecaji elektromagnetskog polja mogu se odraziti na djelovanje upravljačkih uređaja, mjernih uređaja, komunikacijskih kanala itd.

Pravilnicima i zakonom su definirane granične vrijednosti polja kojima se smiju izlagati ljudi koji rade u postrojenjima koja su izvor elektromagnetskih polja, kao i stanovništvo koje živi u blizini postrojenja [5]. Zbog toga je prigodom projektiranja postrojenja potrebno provesti proračun elektromagnetskog polja, te tako provjeriti da li je polje unutar dopuštenih graničnih vrijednosti.

U okviru ovog rada razrađena je teorijska podloga proračuna kvazistatičkog elektromagnetskog polja pomoću integralnih jednadžbi. Rješavanje jednadžbi provodi se metodom momenata. Metoda momenata (MoM), koja se često naziva i metoda rubnih elemenata (BEM), često se koristi u inženjerskim primjenama u dinamici fluida, elektromagnetizmu, termodinamici, akustici itd.

Primjena metode momenata ima nekoliko povoljnih i nepovoljnih karakteristika. U metodi momenata potrebno je diskretizirati samo granicu. To bitno smanjuje broj elemenata i olakšava predprocesiranje. Moguć je jednostavan prijenos iz CAD alata. U metodi momenata jednostavno je modelirati probleme koji uključuju otvorene granice proračuna. Značajna negativna osobina metode momenata je potpuno popunjen sustav jednadžbi. Uz primjenu metode kolokacije ovaj sustav je i nesimetričan. Uz primjenu Galerkinove metode sustav je simetričan, ali zahtijeva provođenje još jedne dodatne integracije vrlo složenih funkcija. Potpuno popunjene matrice sustava uzrokuju dugotrajan proračun.

Na temelju teorijske podloge razvijen je računalni program za trodimenzionalni proračun elektromagnetskog polja. Za proračun elektromagnetskog polja metodom momenata potrebno je odrediti unaprijed nepoznatu razdiobu gustoće naboja i struja na površini vodljivih materijala.
Današnji programi [6], često koriste jednostavne procedure za proračun kvazistatičkog elektromagnetskog polja. Jednostavne procedure podrazumijevaju približenje nepoznate funkcije

1 INTRODUCTION

The electromagnetic fields of industrial frequency is the subject of many works and research studies abroad as well as at home [1], [2], [3] and [4]. The electromagnetic field computation is important in the designing of the electricity transmission and conversion devices. The adverse influences of electromagnetic fields can be reflected on the operation of control systems, measuring instruments, communication channels, etc.

Rules and legislative acts lay down the limit field values that the persons working in the facilities which are the source of electromagnetic fields may be exposed to. The same applies to the population living in the vicinity of such facilities [5]. For that reason, when such facilities are designed it is necessary to make an electromagnetic field computation to check if the field fits into the permissible margins.

This work presents a theoretical groundwork for quasistatic electromagnetic field computation by means of integral equations. The equations are being solved by the method of moments. The method of moments (MoM), also referred to as the boundary element method (BEM), is often used in engineering applications in fluid dynamics, thermodynamics, acoustics, etc.

The application of the method of moments has several favorable and unfavorable features. In the MoM only the boundary ought to be discretized. This significantly reduces the number of elements and facilitates pre-processing. A simple transfer from CAD Tools is possible. Problems which include open boundaries can be simply modeled with the MoM. A markedly negative feature of the MoM is a completely filled system of equations. With the use of the collocation method this system is also non-symmetric. With the use of the Galerkin method the system is symmetric, but requires an extra integration process involving highly complex functions. The completely filled system matrices impose a time-demanding computation.

Based on the mentioned theoretical groundwork, a computer program has been developed for the three-dimensional electromagnetic field computation. For the electromagnetic field computation by the method of moments it is necessary to define the charge and current density distribution, not known in advance, on the surface of conductive materials. The present programs [6] often use simple procedures for the quasistatic electromagnetic field computation. Simple procedures imply the approximation of the unknown source function to the constant values on the boundary elements. Such an approach is advantageous in a relatively simple numerical procedure. However, the approximation of the unknown izvora konstantnim vrijednostima po rubnim elementima. Ovakav pristup ima prednost u relativno jednostavnoj numeričkoj proceduri. Međutim, približenje nepoznate funkcije izvora konstantnim vrijednostima uzrokuje nedovoljnu preciznost. Slaba preciznost može se pokušati kompenzirati vrlo velikim brojem elemenata, što rezultira velikim matricama sustava i praktičnim ograničenjem problema osobito izraženim u 32 – bitnim operativnim sustavima. Polinomnim približenjem funkcije izvora moguće je točnije približiti funkciju izvora i tako smanjiti broj elemenata u sustavu. Razvijene su funkcije polinomne aproksimacije trećeg reda.

Značajan doprinos ubrzanju proračuna ostvaren je paralelizacijom proračuna. Prednosti korištenja paralelnog proračuna su značajne, a proizlaze iz činjenice da su stupci matrice međusobno nezavisni. Nezavisnost stupaca dovodi do jednostavne raspodjele dijelova proračuna po procesorima. Procesor u radnoj stanici, koja je klijent nikad ne čeka rezultate drugog klijenta i u svakom je trenutku raspoloživ za novo opterećenje od strane servera. Zbog nezavisnosti stupaca u metodi momenata, vrlo je jednostavno i uputno koristiti paralelni proračun.

2 TEORIJSKA PODLOGA PRORAČUNA

Izvori električnog i magnetskog polja u okolini prijenosnih vodova su električne struje i raspodjela naboja na vodičima, kao i inducirane struje i naboji u zemlji i objektima u okolini. Početna točka proračuna elektromagnetskog polja promjenjivog u vremenu su Maxwellove jednadžbe. Na frekvenciji 50 Hz polje je kvazistatičko.

Elektromagnetsko polje se tada sastoji od konzervativne komponente električnog polja koju uzrokuje raspodjela naboja po vodičima i rotacijske komponente uzrokovane protjecanjem struja u vodičima. Složene geometrije potrebno je rješavati trodimenzionalnim proračunom.

S obzirom da se promatra polje u točkama udaljenim od vodiča, može se primijeniti tankožično približenje i vodiče nadomjestiti jednodimenzionalnim linijama.

2.1 Proračun konzervativne komponente jakosti električnog polja

U proračunu konzervativnog električnog polja uzimamo u obzir samo vodiče na poznatim (zadanim) potencijalima. Tlo se uzima u proračun kao vodič na nultom potencijalu pa njegov utjecaj modeliramo tehnikom odslikavanja.

source function to the constant values will result in insufficient precision. An attempt may be made to make up for the poor precision with a very great number of elements, which in turn will result in big system matrices and a practical problem limitation, particularly expressed in 32-bit operating systems. With the polynomial approximation of the source function it is possible to approximate the source function more accurately and thus reduce the number of elements in the system. Third-order polynomial approximation functions have been developed.

An important contribution to a speedier computation has been made through computation parallelization. The advantage of using a parallel computation are significant and come from the fact that the matrix columns are mutually independent. The independence of the columns allows an easy distribution of computation parts among the processors. The processor in the workstation which is a client never waits for the results of another client and is available at any time for a new load from the server. Owing to the independence of the columns in the method of moments, the parallel computation is very easy and recommendable for use.

2 A THEORETICAL COMPUTATION GROUNDWORK

The sources of the electrical and magnetic fields in the environment of transmission lines are electric currents and charge distribution on the conductors, as well as induced currents and charges in earth and buildings in the environment. The starting point of computing an electromagnetic field which is variable in time are Maxwell's equations. At 50 Hz frequency the field is quasistatic.

The electromagnetic field consists then of a conservative electric field component caused by charge distribution on the conductors and a rotational component caused by the flow of electric current in the conductors. Complex geometries should be solved by means of the three-dimensional computation.

Since a field is observed in points distant from the conductors, it is possible to apply the thin-wire approximation and to substitute the conductors by one-dimensional lines.

2.1 Computing the conservative electric field strength component

In the conservative electric field computation only the conductors on known (given) potentials are taken into account. The ground is taken in the computation as a conductor on zero potential, so its influence is modeled by the imaging method.

Fazor skalarnog električnog potencijala $\dot{\varphi}(\boldsymbol{r})$ u nekoj točki $\boldsymbol{r}$ na površini vodiča svezan je s fazorom linijske gustoće naboja $\dot{\lambda}(\boldsymbol{r}')$ u proizvoljnoj točki $\boldsymbol{r}'$ na svim tankožičnim dijelovima integralnom jednadžbom:

The scalar electric potential phasor $\dot{\varphi}(\boldsymbol{r})$ on a point $\boldsymbol{r}$ on the conductor's surface is linked with the lineal charge density phasor $\dot{\lambda}(\boldsymbol{r}')$ in an arbitrary point $\boldsymbol{r}'$ on all thin-wire parts by the following integral equation:

$$\dot{\varphi}(\boldsymbol{r}) - \int_l \frac{\dot{\lambda}(\boldsymbol{r}')\,\mathrm{d}l}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|} = 0\,. \tag{1}$$

Za određivanje nepoznate funkcije $\dot{\lambda}(\boldsymbol{r}')$ koristi se metoda momenata [7]. Tanke žice se dijele na segmente konačne veličine Δl_i $(i = 1, ..., N_{\mathrm{seg}})$. Ti segmenti mogu biti dužine, kružni lukovi i dijelovi parabole. Na i – tom konačnom dijelu nepoznatu funkciju $\dot{\lambda}$ se aproksimira s N_{B} temeljnih funkcija t_k kao:

For defining the unknown function $\dot{\lambda}(\boldsymbol{r}')$ the method of moments is used [7]. Thin wires are divided into finite-size segments Δl_i $(i = 1, ..., N_{\mathrm{seg}})$. These segments may be line segments, circular arches and parabola parts. On the i – th final part the unknown function $\dot{\lambda}$ is approximated with N_{B} of base functions t_k as:

$$\dot{\lambda}_i = \sum_{k=1}^{N_{\mathrm{B}}} K_{ik} \cdot t_k\,. \tag{2}$$

Najjednostavniji pristup sastoji se u korištenju temeljnih funkcija koje su konstante na konačnom dijelu ($N_{\mathrm{B}} = 1$). Takav pristup rezultira diskontinuitetima u približenju linijske gustoće naboja i često nezadovoljavajućom točnošću proračuna. Stoga se pretpostavlja kubna ($N_{\mathrm{B}} = 4$) raspodjela na svakom segmentu. Ako se postavi uvjet derivabilnosti na l onda je ovisnost temeljnih funkcija t_k o bezdimenzionalnom parametru χ $(1 \geq \chi \geq 0)$ definirana kao:

The easiest approach is to use the base functions which are constant on the finite segment ($N_{\mathrm{B}} = 1$). Such an approach results in discontinuities in the approximation of the lineal charge density and in an often unsatisfactory computation accuracy. Hence the cubic ($N_{\mathrm{B}} = 4$) distribution on each segment has been chosen. If the derivability condition is set on l then the dependence of the base functions t_k on the non-dimensional parameter χ $(1 \geq \chi \geq 0)$ is defined as:

$$t_k = \sum_{j=1}^{4} a_{kj} \cdot \chi^{j-1};\ k = 1,2,3,4\,. \tag{3}$$

Koeficijenti a_{kj} su sadržani u matrici $[A]$:

Coefficients a_{kj} are contained in matrix $[A]$:

$$\boldsymbol{A} = \begin{bmatrix} 1 & 0 & -3 & 2 \\ 0 & 1 & -2 & 1 \\ 0 & 0 & 3 & -2 \\ 0 & 0 & -1 & 1 \end{bmatrix}. \tag{4}$$

Sada se $\dot{\lambda}$ može izraziti pomoću:

Now $\dot{\lambda}$ can be expressed by means of:

$$\dot{\lambda}_i(s) = \sum_{k=1}^{4} K_{ik} \sum_{j=1}^{4} a_{kj} \cdot \chi^{j-1}, \tag{5}$$

gdje je:

where:

$$K_{i1}=\dot{\lambda}_i(0)\,;\quad K_{i2}=\frac{\mathrm{d}\,\dot{\lambda}_i}{\mathrm{d}\,\chi}\bigg|_{\chi=0}\,,$$
$$K_{i3}=\dot{\lambda}_i(1)\,;\quad K_{i4}=\frac{\mathrm{d}\,\dot{\lambda}_i}{\mathrm{d}\,\chi}\bigg|_{\chi=1}\,. \tag{6}$$

Supstitucija izraza (5) u (1) rezultira s:

Substitution of expression (5) into (1) results in:

$$\dot{\varphi}(\boldsymbol{r})=\sum_{i=1}^{N_{\mathrm{seg}}}\left[\sum_{k=1}^{2}K_{ik}\int_{\Delta l_i}\frac{t_k(\boldsymbol{r}')\mathrm{d}\,l}{4\,\pi|\boldsymbol{r}-\boldsymbol{r}'|}+\sum_{k=1}^{2}K_{i+1,k-2}\int_{\Delta l_i}\frac{t_k(\boldsymbol{r}')\mathrm{d}\,l}{4\,\pi|\boldsymbol{r}-\boldsymbol{r}'|}\right]. \tag{7}$$

Sustav linearnih algebarskih jednadžbi za nepoznate kompleksne koeficijente K_{ik} dobiva se usklađivanjem u točkama. Pokusne točke se nalaze na jednoj i dvije trećine svakog segmenta. Linijske se integrale u (7) računa numerički primjenom adaptivnog algoritma koji se temelji na Gauss-Kronrodovim pravilima. Rješenje sustava definira diferencijabilno približenje linijskog naboja $\dot{\lambda}$ na svakom segmentu. Nakon toga, pomoću izraza:

The system of linear algebraic equations for the unknown complex coefficients K_{ik} is obtained by the point matching methods. The collocation points are located on one and two thirds of each segment. The line integrals in (7) are computed numerically using an adaptive scheme based on Gauss-Kronrod rules. The system solution defines the differential approximation of the lineal charge $\dot{\lambda}$ on each segment. After that, by means of the expression:

$$\dot{\boldsymbol{E}}(\boldsymbol{r})=\sum_{i=1}^{N_{seg}}\left[\sum_{k=1}^{2}K_{ik}\int_{\Delta l_i}\frac{t_k(\boldsymbol{r}')(\boldsymbol{r}-\boldsymbol{r}')\mathrm{d}\,l}{4\,\pi|\boldsymbol{r}-\boldsymbol{r}'|^3}+\sum_{k=3}^{4}K_{i+1,k-2}\int_{\Delta l_i}\frac{t_k(\boldsymbol{r}')(\boldsymbol{r}-\boldsymbol{r}')\mathrm{d}\,l}{4\,\pi|\boldsymbol{r}-\boldsymbol{r}'|^3}\right], \tag{8}$$

može se izračunati vektor-fazor konzervativne komponente jakosti električnog polja u točki $\boldsymbol{r}$.

it is possible to compute the vector-phasor of the conservative electric field strength component in point $\boldsymbol{r}$.

2.2 Proračun rotacijske komponente elektromagnetskog polja

Promatra se linearni izotropni poluprostor V_{e} sa značajkama $\varepsilon=\varepsilon_0$, $\mu=\mu_0,\gamma$ koji se nalazi u slobodnom prostoru V_0. Regija V_{e} je ograničena s ravninom S_{e} s jediničnim vektorom okomice $\boldsymbol{n}$. Vanjska pobuda ($\dot{\boldsymbol{B}}_{\mathrm{e}}$, $\dot{\boldsymbol{E}}_{\mathrm{e}}$) koju uzrokuju struje u vodičima računa se pomoću izraza (9) i (10):

2.2 Computing the rotational components of electromagnetic fields

Under observation is the linear isotropic semi-space V_{e} with characteristics $\varepsilon=\varepsilon_0$, $\mu=\mu_0,\gamma$ situated in the free space V_0. Region V_{e} is bounded by plane S_{e} with normal unit vector $\boldsymbol{n}$. The external excitation ($\dot{\boldsymbol{B}}_{\mathrm{e}}$, $\dot{\boldsymbol{E}}_{\mathrm{e}}$) caused by electric currents in the conductors is computed by means of expressions (9) and (10):

$$\dot{\boldsymbol{B}}_{\mathrm{e}}=\int\frac{\mu\cdot\dot{I}\,\mathrm{d}\,\boldsymbol{l}\times(\boldsymbol{r}-\boldsymbol{r}')}{4\,\pi|\boldsymbol{r}-\boldsymbol{r}'|}\,, \tag{9}$$

$$\dot{\boldsymbol{E}}_{\mathrm{e}}=\mathrm{j}\omega\int\frac{\mu\cdot\dot{I}\,\mathrm{d}\,\boldsymbol{l}}{4\,\pi|\boldsymbol{r}-\boldsymbol{r}'|}\,. \tag{10}$$

Elektromagnetsko polje u prostoru V_0 se može izračunati iz jednadžbi (11) i (12):

Electromagnetic field in space V_0 can be computed from the equations (11) and (12):

$$c \cdot \boldsymbol{E} = \boldsymbol{E}_{\mathrm{e}} + \int_S \left[(\boldsymbol{n} \cdot \boldsymbol{E}) \cdot \nabla G_1 + (\boldsymbol{n} \times \boldsymbol{E}) \times \nabla G_1 + (\boldsymbol{n} \times \nabla \times \boldsymbol{E}) G_1 \right] \mathrm{d}S , \tag{11}$$

$$c \cdot \boldsymbol{B} = \boldsymbol{B}_{\mathrm{e}} + \int_S \left[(\boldsymbol{n} \cdot \boldsymbol{B}) \cdot \nabla G_1 + (\boldsymbol{n} \times \boldsymbol{B}) \times \nabla G_1 + (\boldsymbol{n} \times \nabla \times \boldsymbol{B}) G_1 \right] \mathrm{d}S . \tag{12}$$

Pri tom je $c = 1$ za $\boldsymbol{r} \in V_0$, a $c = \frac{1}{2}$ za $\boldsymbol{r} \in S$

U jednadžbe (11) i (12) se uvodi na granici dva prostora izraz za induciranu električnu struju $\dot{\boldsymbol{K}}_{\mathrm{S}}$, induciranu magnetsku struju $\dot{\boldsymbol{M}}_{\mathrm{S}}$ i električni naboj $\dot{\rho}_{\mathrm{e}}$:

where $c = 1$ za $\boldsymbol{r} \in V_0$, a $c = \frac{1}{2}$ za $\boldsymbol{r} \in S$.

On the boundary of two spaces the expression for induced electric current $\dot{\boldsymbol{K}}_{\mathrm{S}}$, induced magnetic current $\dot{\boldsymbol{M}}_{\mathrm{S}}$ and electric charge $\dot{\rho}_{\mathrm{e}}$ is introduced into equations (11) and (12) :

$$\dot{\boldsymbol{K}}_{\mathrm{S}}(\boldsymbol{r}) = \boldsymbol{n} \times \dot{\boldsymbol{H}}_1(\boldsymbol{r}) \ , \tag{13}$$

$$\dot{\boldsymbol{M}}_{\mathrm{S}}(\boldsymbol{r}) = -\boldsymbol{n} \times \dot{\boldsymbol{E}}_1(\boldsymbol{r}) \ , \tag{14}$$

$$\dot{\rho}_{\mathrm{e}} = \boldsymbol{n} \cdot \boldsymbol{E}_1 \varepsilon_0 \ . \tag{15}$$

Jednadžbe (11) i (12) mogu se tako napisati u obliku:

Equations (11) and (12) can thus be written as follows:

$$\dot{\boldsymbol{B}}_1(\boldsymbol{r}) = \dot{\boldsymbol{B}}_{\mathrm{e}}(\boldsymbol{r}) + \mu_0 \int_S \dot{\boldsymbol{K}}_{\mathrm{S}} \times \nabla' G_1 \, \mathrm{d}S' + \mathrm{j} \frac{1}{\omega} \int_S \nabla \cdot \dot{\boldsymbol{M}}_{\mathrm{S}} \nabla' G_1 \, \mathrm{d}S' , \tag{16}$$

$$\dot{\boldsymbol{E}}_1(\boldsymbol{r}) = \dot{\boldsymbol{E}}_{\mathrm{e}}(\boldsymbol{r}) - \mathrm{j}\omega\mu_0 \int_S \dot{\boldsymbol{K}}_{\mathrm{S}} G_1 \, \mathrm{d}S' + \int_S \dot{\boldsymbol{M}}_{\mathrm{S}} \times \nabla' G_1 \, \mathrm{d}S' + \frac{1}{\varepsilon_0} \int_S \dot{\rho}_{\mathrm{e}} \nabla' G_1 \, \mathrm{d}S' . \tag{17}$$

Greenova funkcija G_1 definirana je izrazom (18):

Green's function G_1 is defined by expression (18):

$$G_1 = \frac{1}{4\pi |\boldsymbol{r} - \boldsymbol{r}'|} \ . \tag{18}$$

Iz uvjeta na granici V_0 i V_{e} određuju se inducirane struje i naboji prema izrazima (19), (20) i (21):

From the conditions on the boundary of V_0 and V_{e}, the induced currents and charges are are obtained using expressions (19), (20) and (21):

$$\begin{gathered} \boldsymbol{n} \times \left(\int_S (\mu_0 G_1 - \mu_0 G_2) \times \dot{\boldsymbol{K}}_{\mathrm{S}} \, \mathrm{d}S' \right) + \boldsymbol{n} \times \left(\int_S \mu_0 \cdot \gamma \cdot G_2 \cdot \dot{\boldsymbol{M}}_{\mathrm{S}} \, \mathrm{d}S' \right) + , \\ \boldsymbol{n} \times \frac{1}{\mathrm{j}\omega} \int_S (\nabla G_1 - \nabla G_2) \nabla' \cdot \dot{\boldsymbol{M}}_{\mathrm{S}} \, \mathrm{d}S' - \mu_0 \dot{\boldsymbol{K}}_{\mathrm{S}} = -\boldsymbol{n} \times \dot{\boldsymbol{B}}_{\mathrm{e}} \end{gathered} \tag{19}$$

$$
\boldsymbol{n}\times\left(-\mathrm{j}\omega\mu_0\int_S (G_1-G_2)\dot{\boldsymbol{K}}_\mathrm{S}\,\mathrm{d}S'\right)-\boldsymbol{n}\times\left(\int_S (G_1-G_2)\times\dot{\boldsymbol{M}}_\mathrm{S}\,\mathrm{d}S'\right)-
$$

$$
\boldsymbol{n}\times\int_S \nabla G_1\frac{\dot{\rho}_\mathrm{e}}{\varepsilon_0}\mathrm{d}S'+\dot{\boldsymbol{M}}_\mathrm{S}=-\boldsymbol{n}\times\dot{\boldsymbol{E}}_\mathrm{e} \quad , \tag{20}
$$

$$
\boldsymbol{n}\cdot\left(-\mathrm{j}\omega\mu_0\int_S (G_1-G_2)\dot{\boldsymbol{K}}_\mathrm{S}\,\mathrm{d}S'\right)-\boldsymbol{n}\cdot\left(\int_S (G_1-G_2)\times\dot{\boldsymbol{M}}_\mathrm{S}\,\mathrm{d}S'\right)-
$$

$$
\boldsymbol{n}\cdot\int_S \nabla G_1\frac{\dot{\rho}_\mathrm{e}}{\varepsilon_0}\mathrm{d}S'-\frac{\dot{\rho}_\mathrm{e}}{2\varepsilon_0}=-\boldsymbol{n}\cdot\dot{\boldsymbol{E}}_\mathrm{e} \quad . \tag{21}
$$

Greenova funkcija G_2 definirana je izrazom (22):

Green's function G_2 is defined by expression (22):

$$
G_2=\frac{\mathrm{e}^{-\mathrm{j}k|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|} \quad . \tag{22}
$$

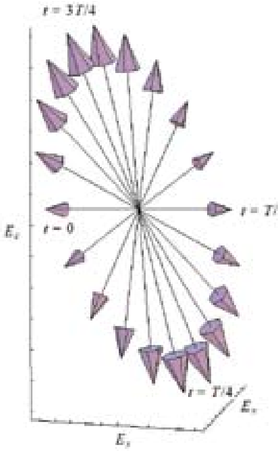
2.3 Prikaz rezultata proračuna

U trodimenzionalnom proračunu vektor jakosti električnog polja je u svakoj točki eliptički polariziran, što znači da vrh vektora $\boldsymbol{E}$ u vremenu opisuje elipsu (slika 1) budući da svaka od triju komponenata općenito ima različitu veličinu i fazni pomak. Za komponente vektora električnog polja vrijedi izraz (23):

2.3 Presentation of computation results

In a three-dimensional computation the electric field strength vector is elliptically polarized in every point, meaning that the terminal point $\boldsymbol{E}$ in time determines the ellipse (Figure 1), because each of the three components generally has a different size and phase shift. Expression (23) applies to the electric field vector components:

$$
\begin{aligned}
E_x(t)&=E_{x,\max}\cos(\omega t+\varphi_x),\\
E_y(t)&=E_{y,\max}\cos(\omega t+\varphi_y),\\
E_z(t)&=E_{z,\max}\cos(\omega t+\varphi_z).
\end{aligned} \tag{23}
$$



Slika 1 — Eliptički polarizirano električno polje

Figure 1 — Elliptically polarized electric field

Efektivna vrijednost vektora električnog i magnetskog polja koristit će se kao rezultat proračuna električnog i magnetskog polja (24):

The effective value of the electric and magnetic filed vectors will be used as a result of the electric and magnetic field computation (24):

$$E=\sqrt{\frac{E^2_{x,\max}+E2_{y,\max}+E^2_{z,\max}}{2}}\ . \tag{24}$$

3 PRORAČUN ELEKTROMAGNETSKOG POLJA

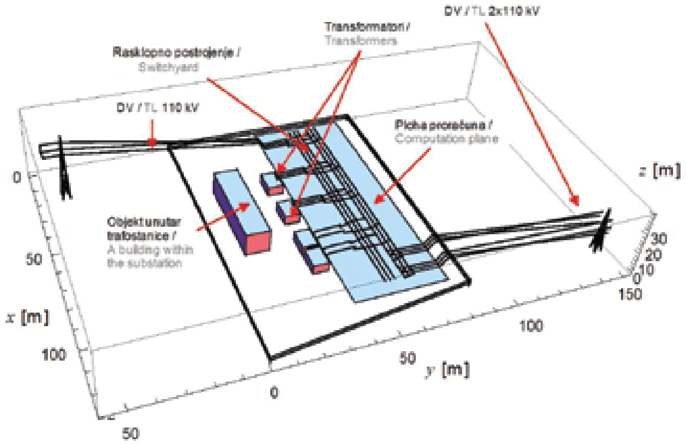
Primjer proračuna elektromagnetskog polja proveden je za 110 kV transformatorsku stanicu prikazanu slikom 2.

Jakost električnog polja i magnetska indukcija računaju se na plohi na visini 2m iznad zemlje. Napon na vodičima vanjskog visokonaponskog postrojenja je 110kV. Za proračun rotacijske komponente elektromagnetskog polja koriste se vrijednosti maksimalne struje opterećenja vodiča $I_\mathrm{v}=645\ \mathrm{A}$, odnosno struje na sabirnicama $I_\mathrm{sab}=1\ 290\ \mathrm{A}$.

3 ELECTROMAGNETIC FIELD COMPUTATION

An example of the electric field computation has been carried out for the 110 kV substation shown in Figure 2.

Electric field strength and magnetic induction are computed on a plane at 2 m height above ground level. Voltage on the conductors of an external high-tension facility stands at 110 kV. Used for computing the rotational electromagnetic field component are the values of maximal conductor load current $I_\mathrm{v}=645\ \mathrm{A}$, or busbar currents $I_\mathrm{sab}=1\ 290\ \mathrm{A}$.

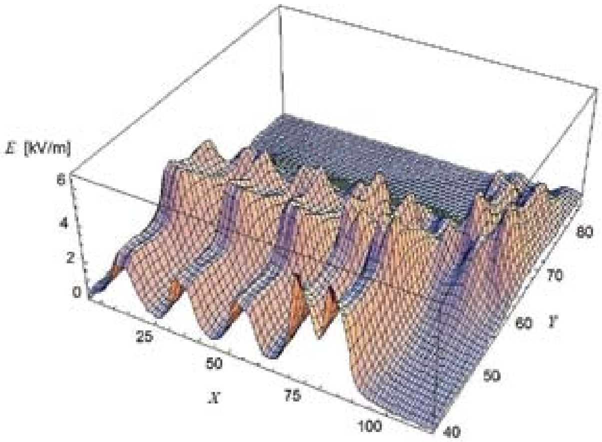


Slika 2 — Model transformatorske stanice

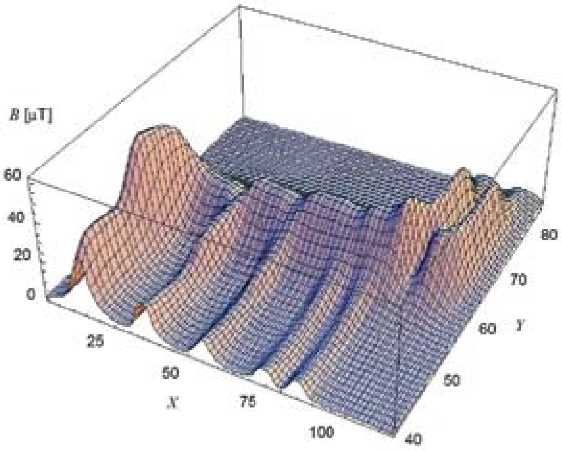
Figure 2 — Substation model

Jakost električnog polja na horizontalnoj plohi proračuna na visini 2 m iznad zemlje unutar postrojenja prikazana je slikom 3.

The electric field strength on the horizontal computation plane at 2 m height above ground level within the facility is shown in Figure 3.



Slika 3 — Jakost električnog polja na visini 2 m iznad zemlje
Figure 3 —Electric field strength at 2 m height above ground



Slika 4 — Magnetska indukcija na visini 2 m iznad zemlje
Figure 4 —Magnetic induction at 2 m height above ground

4 ZAKLJUČAK

Točan proračun niskofrekvencijskih kvazistatičkih elektromagnetskih polja značajan je za projektiranje naprava za prijenos i pretvorbu električne energije. U okviru ovog rada razrađena je teorijska podloga proračuna pomoću integralnih jednadžbi. Postupci rješavanja tih jednadžbi definirani su primjenom metode momenata i tankožičnog približenja vodiča. Nepoznata raspodjela gustoće naboja u proračunu bezvrtložne komponente električnog polja je aproksimirana krivuljama trećeg reda. Vrtložna komponenta elektromagnetskog polja je određena iz zadanih struja uzimajući u obzir utjecaj induciranih vrtložnih struja u vodljivim materijalima. Primjenjivost razvijenih postupaka pokazana je proračunom kvazistatičkog elektromagnetskog polja u primjeru iz prakse.

4 CONCLUSION

A precise computation of low-frequency quasistatic electromagnetic fields is important when it comes to designing the electricity transmission and conversion devices. This work presents a theoretical groundwork for computation by means of integral equations. The procedures for solving these equations are defined by applying the method of moments and the point matching method. The unknown distribution of charge density in the computation of the non-eddy component of an electric field is approximated by third-order curves. The eddy component of an electromagnetic field is defined from given currents taking into account the impact of induced eddy currents in conductive materials. The applicability of the developed procedures is demonstrated on a practical example through the computation of a quasistatic electromagnetic field.

Točnijom aproksimacijom nepoznatih raspodjela gustoće inducirane struje i naboja na granicama vodljivih materijala moguće je točnije odrediti i jakost električnog polja i magnetsku indukciju u prostoru.

A more accurate approximation of unknown density distributions of induced current and charge on the boundaries of conductive materials will allow a more accurate definition of both the electric field strength and the magnetic induction in space.

LITERATURA / REFERENCES

[1] ŠTIH, Ž., TRKULJA, B., BERBEROVIĆ, S., Computation of Low-Frequency Electric Fields in Computation of Low-Frequency Electric Fields in Analysis of Electromagnetic Field Exposure , 9th Spanish Portuguese Congress on Electrical Engineering (9CHLIE) Proceedings, Marbella, 2005

[2] ŠTIH, Ž., TRKULJA, B., Computation of Low-frequency Electromagnetic Field Near Transmission Lines and Substations , Proceedings of the 10th International Symposium on Numerical Field Calculation in Electrical Engineering. Graz : Graz University of Technology, 2002

[3] ŠTIH, Ž., TRKULJA, B., Application of Bicubic Splines in the Boundary Element Method , Proceedings of the 16th Conference on the Computation of Electromagnetic Fields COMPUMAG 2007 Dular, Patrick ; Kurz, Stefan (ur.).Aachen : IEM RWTH , 2007

[4] TRKULJA, B., Proračun elektromagnetskog polja složenih elektroenergetskih objekata, doktorska disertacija, Zagreb, 2008.

[5] Pravilnik o zaštiti od elektromagnetskih polja, Narodne novine 204/2003

[6] EFC 400 Magnetic and Electric Fields Calculation, Users Manual, Narda Safety Test Solutions, Berlin, 2006

[7] Haznadar, Z., Štih, Ž., Elektromagnetizam 1 i 2, Školska knjiga, Zagreb, 1997.

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