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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 treći broj časopisa Energija u 2009. godini. Fenomen recesije, koji nije zaobišao niti razvojno investicijski ciklus u energetici, jedan je od uzroka smanjenog ulaganja u izgradnju novih energetskih objekata. S druge strane, iako je potrošnja energije niža nego je to bilo planirano, potencijal potrošnje energije odnosno porasta potrošnje energije ostao je jednak kao i prijašnjih godina. Znači li to da bi se u kratkom razdoblju nakon oporavka financijskih institucija mogli naći u situaciji nemogućnosti dobave potrebnih količina energije poradi nedovoljnih proizvodnih i transportnih odnosno prijenosnih kapaciteta. Ne treba posebno naglašavati kako je to potencijalno opasna situacija koja u krajnjem slučaju može dovesti do ograničenja u isporuci energije ili do nekontroliranog porasta cijena energije. Pozivamo vas da u slijedećim brojevima časopisa Energija iznesete, između ostalih, i svoja promišljanja na temu vezanu uz sigurnost dobave energije nakon pokretanja novog razvojno investicijskog ciklusa koji neminovno slijedi nakon razdoblja recesije.

U ovom broju časopisa Energija objavljujemo vrlo zanimljive članke iz različitih područja, od energetskih do specijalističkih područja elektrotehnike:

- Upravljanje životnim vijekom kabela kao dio programa produljenja životnog vijeka nuklearne elektrane,
- Prioritizacija projekata regionalne prijenosne mreže u svrhu potpore proizvodnje i razvoja tržišta u jugoistočnoj Europi,
- Eksperimentalni ferorezonantni krug kao fizički model ferorezonantnog dijela elektroenergetske mreže,
- Točniji proračun magnetskih gubitaka u asinkronom motoru,
- Određivanje matrice koeficijenata redukcije sustava kabelskih vodova.

U prvom članku daje se prikaz Programa upravljanja životnim vijekom (engl. *Aging management programme* – AMP) koji ima za cilj ocjenu stanja nekih važnih komponenti nuklearne elektrane. U ovom članku se konkretnije obrađuje problem upravljačkih i instrumentacijskih kabela za koje se drži da su jedne od komponenti ključnih za siguran rad nuklearnih elektrana. Cilj ovog Programa je identificiranje mehanizama i učinaka starenja na upravljačke i instrumentacijske kabele te utvrđivanje stupnja degradacije uzrokovane starenjem kako bi se utvrdilo je li degradacija unutar dopuštenih granica. Poopćili se ova koncepcija, možemo reći kako članak opisuje neke od važnih aktivnosti koje će se poduzeti u narednih desetak godina kako bi se utvrdila mogućnost produljenja životnog vijeka nuklearnih elektrana koje su ušle u pogon sedamdesetih godina.

Drugi članak pokazuje rezultate analize mogućnosti odnosno potrebe izgradnje prijenosnih interkonektivnih vodova između elektroenergetskih sustava zemalja jugoistočne Europe. Rezultati analiza temelje se na nekoliko istraživanja provedenih u zadnjih nekoliko godina u okviru Atenskog foruma, ponajprije se to odnosi na studiju GIS (*Generation Investment Study*) koja je na temelju određenih pojednostavljenih pretpostavki dala prikaz mogućno-

Dear readers!

Before you is the third edition of Energija for the year 2009. The recession phenomenon, which has also touched the development and investment cycle in the energy sector, is one of the lead causes of reduced investments in the constructions of new power plants. On the other hand, despite the fact that energy consumption is lower than predicted, the potential of energy consumption, that is, the rise in energy consumption has remained the same as in the previous years. Does this mean that in a very short time after the recovery of financial institutions we might find ourselves unable to supply the necessary amounts of energy due to insufficient production and transport, i.e. transmission capacities? There is no need to stress the fact that this presents a potentially dangerous situation which, in the end, could lead to limited energy supply or uncontrolled growth of energy prices. We invite you to share with us, in the following editions of Energija, among other, your thoughts on the subject of power supply security after the launch of the new development and investment cycle which will inevitably follow the recession.

In this issue of Energija, we present very interesting articles from various fields, from the energy-related to specialist electrical engineering fields:

- Cable lifespan management as part of the programme of extending the nuclear power plant lifespan,
- Priorization of regional transmission network projects for the purpose of production and development of the market in southeast Europe,
- Experimental ferroresonance circuit as the physical model of the ferroresonance part of the electrical power network,
- A more accurate calculation of magnetic losses in the asynchronous motor,
- Determination of the cable duct system reduction coefficient matrix.

The first article provides an overview of the Aging Management Programme (AMP) whose purpose is to evaluate the conditions of some important nuclear power plant's components. This article deals in more detail with the problem of control and instrumentation cables, which are considered one of the key components of safe nuclear power plant functioning. This programme's objective is to identify the aging mechanisms and the effects they have on control and instrumentation cables as well as to determine the degradation stage caused by aging in order to find out whether the degradation is within the tolerated limits. If we generalize this concept, one might say that the article describes some of the important activities which will be undertaken in the next ten years in order to determine the possibility of the extension of nuclear power plant lifespan, which started operating in the seventies.

The second article shows the analysis results of the possibility, i.e. the need to set up transmission interconnection lines between the electrical power systems of the countries of Southeast Europe. The analysis results are based on several researches conducted in the last few years within the Athens forum, notably the GIS study (Generation Investment Study) which was able to provide an overview of the possibilities and the need for the construction of new production facilities on the grounds of sti i potrebe izgradnje novih proizvodnih postrojenja. Temeljem novelacije te studije kao i novih spoznaja specificiranih u članku, izrađena je lista prioriteta za gradnju interkonektivnih vodova u regiji uz poseban komentar za svaki odabrani vod. Članak obiluje podacima vezanim uz analizirane interkonekcije i u cjelini uzevši, predstavlja vrlo vrijedan doprinos razumijevanju stanja i perspektiva razvoja elektroenergetskih sustava zemalja u jugoistočnoj Europi.

Treći članak opisuje eksperimentalno mjerenje fenomena ferorezonancije koja se može pojaviti u praksi i koja može uništiti dijelove elektroenergetske mreže. Upravo stoga je važan svaki pokušaj eksperimentalnog istraživanja ferorezonancije na ferorezonantnim dijelovima elektroenergetske mreže i u ovom članku su opisana istraživanja eksperimentalnog ferorezonantnog kruga na temelju vrijednosti parametara 230 kV transformatorske stanice Dorsey (Manitoba, Kanada). Laboratorijska istraživanja urađena su na Elektrotehničkom fakultetu Sveučilišta u Osijeku. Usporedbom normiranih parametara i rezultata mjerenja eksperimentalnog ferorezonantnog kruga 230 kV transformatorske stanice Dorsey zaključeno je da se eksperimentalni ferorezonantni krug može koristiti kao fizički model ferorezonantnog dijela elektroenergetske mreže. Na opisani bi se način mogao realizirati fizički model ferorezonantnih dijelova elektroenergetske mreže a najznačajniji problem autori vide u definiranju vrijednosti parametara mreže značajnih za ovu pojavu.

Četvrti članak opisuje jedan zanimljiv aspekt elektromotornih pogona kojemu se, iako od samih početaka, pridaje posebna pozornost u zadnje vrijeme. Elektromotorni pogoni čine oko 70 % industrijskih trošila, pa se trend povećanja energetske korisnosti elektromotornih pogona, ne samo s ekonomskog već i s ekološkog stanovišta, odrazio i na proučavanje gubitaka asinkronih motora. Bitan parametar energetske korisnosti asinkronih motora predstavljaju gubici energije u magnetskim materijalima. U radu se razrađuje analitički proračun pa se temeljem usporedbe rezultata analitičkog proračuna gubitaka i rezultata mjerenja te usporedbom s numeričkim proračunom, prednost ipak daje analitičkom proračunu za koji je opet, kako tvrde autori, potrebno inženjersko iskustvo projektiranja.

U zadnjem, petom članku u ovom broju časopisa Energija donosimo vrlo zanimljive izvorne teorijske podloge matematičkog modela za određivanje matrice koeficijenata redukcije sustava kabelskih vodova. Riječ je o novom i posve općenitom matematičkom modelu koji može uvažiti proizvoljan broj i raspored sustava jednožilnih kabela složenih u trokutnom snopu. Naime, u sustavu kabelskih vodova, u uvjetima nastupa jednopolnoga kratkog spoja, dolazi do međusobne elektromagnetske sprege među pripadnim kabelskim vodovima. To utječe na raspodjelu popratne struje kvara u pripadnom sustavu uzemljenja, kao i u samoj zemlji. U članku je prikazan model koji je jednostavan za primjenu i posve općenit. Posebnu vrijednost predstavlja i primjena prezentirane teorije i razvijenog matematičkog modela prikazana na primjeru općeg sustava kabelskih vodova nazivnog napona 110 kV.

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

simplified postulates. Based on the novelation of the stated study as well as new understandings mentioned in the article, a list of priorities was made for the construction of interconnection lines in the region with a specific comment for each selected line. The article abounds in data related to the analysed interconnections, and as a whole, represents a highly valuable contribution for understanding the situation of development and the perspectives of the electric power system in the countries of Southeast Europe.

The third article describes experimental measuring of the ferroresonace phenomenon which may appear in practice and which can destroy parts of the electrical power network. This is why each attempt of experimental research of ferroresonance on ferroresonant parts of the electrical power network is highly important. This article describes researches on experimental ferroresonant circuits on the grounds of parameter value of 230 kV of the Dorsey substation (Manitoba, Canada). Laboratory researches were conducted at the Faculty of Electrical Engineering in Osijek. By comparing the standardized parameters and measuring results of the experimental ferroresonant circuit of 230 kV in the transformer station Dorsery, a conclusion has been made that the experimental ferroresonant circuit may be used as a physical model of ferroresonant part of the electrical power network. The manner described might be the way to realize the physical model of ferroresonant parts of the electrical power network, while the authors regard the defining of parameters, important for this phenomenon, as the most significant problem.

The fourth article describes an interesting aspect of electromotor drives which have found themselves in the spotlight lately, although they have raised interest since the very beginnings. Electromotor drives make up about 70 % of industrial use and so the trend of increase of energetic efficiency of electromotor drives, not only from the economic but also from the environmental standpoint, had a significant effect on the study of asynchronous motor losses. Energy losses in magnetic materials represent an important parameter of energy efficiency of asynchronous motors. The work elaborates on the analytic calculation; therefore, based on comparison of the results of the analytical calculation and the measurement results as well as comparison with the results of the numerical calculation, the advantage is still on the side of the analytical calculation which, according to the authors, requires engineering experience.

The last, fifth article in this edition of the Energija brings very interesting original theoretical bases of the mathematical model for the determination of the cable duct system reduction coefficient matrix. The matter at hand is a new and completely general mathematical model which can take into consideration an arbitrary number and arrangement of a one-core cable system arranged in a triangular truss. Namely, in the cable duct system, in the conditions of occurrence of a one-pole short circuit, there occurs reciprocal electromagnetic coupling between the pertaining cable ducts. That affects the distribution of the accompanying fault current in the pertaining earthing system, as well as in the ground itself. The article presents a model which is simple for application and entirely general in its nature. Especially valuable is also the application of the presented theory and the developed mathematical model shown on the example of the general system of cable ducts with a nominal voltage 110 kV.

The articles in this issue of Energija were written by the authors both from the academic community and from practice which surely resulted in articles of high quality as well.

Editor-in-chief:
Goran Slipac, MSc

UPRAVLJANJE ŽIVOTNIM VIJEKOM KABELA KAO DIO PROGRAMA PRODULJENJA ŽIVOTNOG VIJEKA NUKLEARNE ELEKTRANE

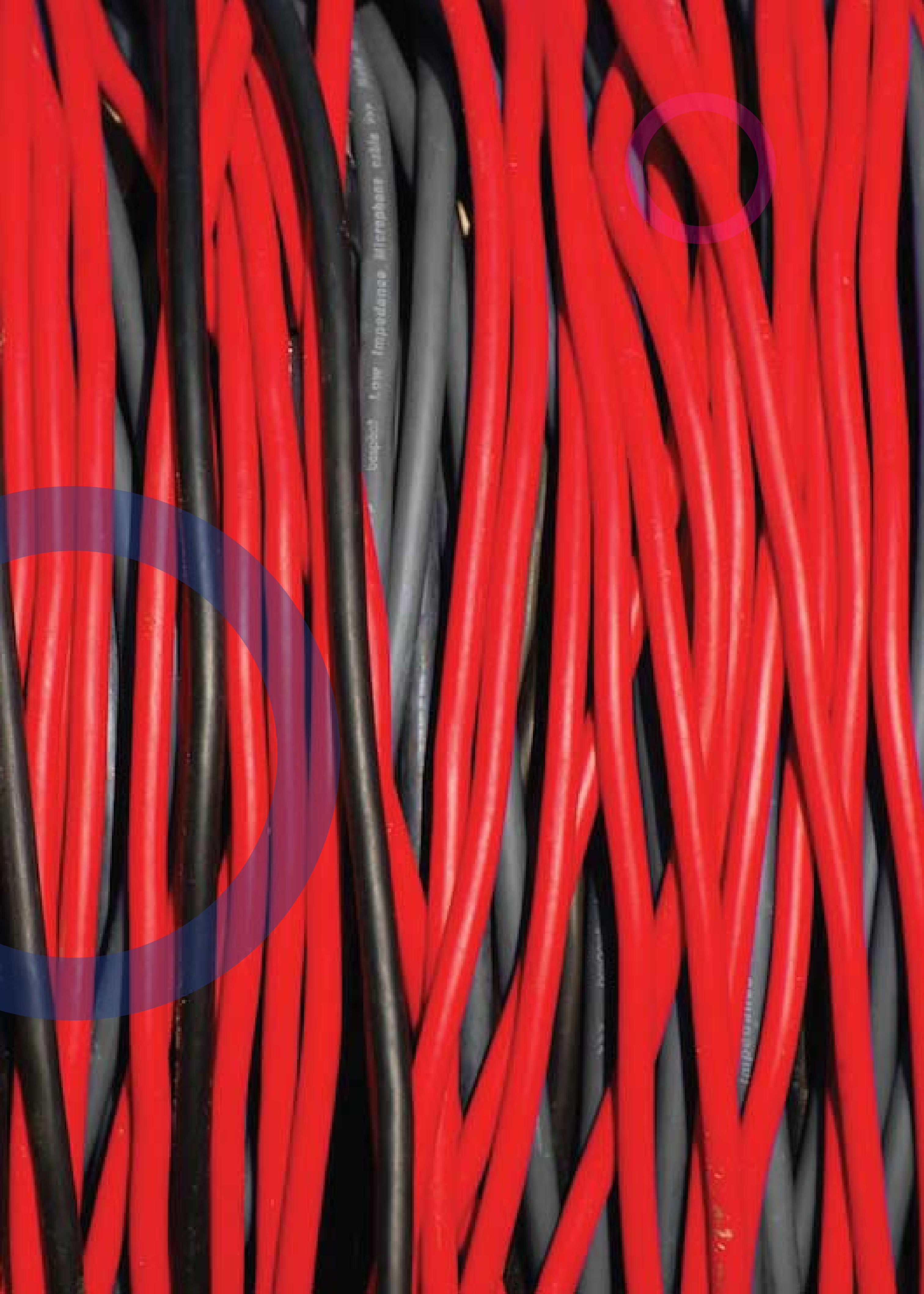
CABLE AGING MANAGEMENT AS PART OF THE EXTENDED NUCLEAR POWER PLANT LIFESPAN PROGRAMME

Nikola Čavlina – Irena Jakić – Renato Barbarić, Zagreb, Hrvatska
Bruno Glaser, Krško, Slovenija

Članak daje sveobuhvatan pregled procesa starenja kabela, od identifikacije mehanizama i procjene starenja te učinka na sigurnost nuklearnih elektrana do upravljanja samim procesom. Cilj je zaokružiti temu iz različitih perspektiva i dati informacije i zaključke utemeljene na iskustvu i pouzdanim rezultatima mjerenja.

The article provides a comprehensive overview of the cable aging process, from mechanism identification and aging assessment and the effect on nuclear power plants' safety to the management of the process itself. The objective is to round up the subject from different perspectives and provide information and conclusions based on experience and reliable measurement results.

Ključne riječi: kabeli; nuklearna elektrana; produljenje životnog vijeka; sigurnost nuklearnih elektrana; starenje kabela
Key words: cables; cable aging; extended lifespan; nuclear power plant; nuclear power plants' safety


Low Impedance Microphone cable

1 UVOD

U svijetu je, prema podacima Međunarodne agencije za atomsku energiju, početkom 2009. godine bilo u pogonu ukupno 436 nuklearnih reaktora. Najveći je broj tih reaktora započeo s radom u 1970-tim godinama i većina je imala projektom predviđeni životni vijek od 30 do 40 godina.

Te se elektrane približavaju kraju početno predviđenog životnog vijeka, a istodobno rade dobro i konkurentne su. Stoga postoji veliki interes za produljenjem njihovog vijeka eksploatacije. Razlozi su prvenstveno ekonomski jer su kapitalni troškovi za produljenje životnog vijeka tih elektrana neusporedivo manji od troškova izgradnje bilo kojih drugih zamjenskih kapaciteta.

Međutim, potrebno je utvrditi da li starenju izložene komponente, strukture i sustavi nuklearne elektrane mogu ispuniti svoje projektom predviđene funkcije i u slučaju produljenja vijeka eksploatacije. Starenje opreme se može definirati kao kontinuirana, vremenski ovisna degradacija materijala zbog uvjeta rada, kako u normalnom pogonu, tako i u tranzijentnim uvjetima.

Redundancija i diverzifikacija su principi projektiranja sigurnosnih sustava nuklearne elektrane, kojima se osigurava da i pri pojavi slučajnog kvara barem jedan sigurnosni sustav ispunjava projektom predviđenu funkciju. Bojazan je da se zbog starenja opreme u slučaju dodatnih opterećenja na opremu ne desi simultani kvar u kritičnom vremenu. Takav bi kvar, u kombinaciji starenja i akcidentalnih ambijentalnih uvjeta, imao obilježja kvara sa zajedničkim uzrokom (engl. *Common cause failure*) i mogao bi učiniti neraspoloživim sve redundantne sustave, a kad su u pitanju električni kabeli, ni diverzitet u izvedbi sigurnosnog sustava ne bi puno pomogao.

Programom upravljanja životnim vijekom (engl. *Aging management programme* – AMP) na odgovarajući se način upravlja učincima starenja sustava, struktura i komponenti nuklearne elektrane. Posebna se pažnja posvećuje onim sustavima i komponentama koji nisu predmet redovnog održavanja. Cilj je identificiranje mehanizama i učinaka starenja, te utvrditi jesu li degradacije uzrokovane starenjem unutar dopuštenih granica, kako bi se osigurao siguran rad elektrane za budući period.

Program AMP uobičajeno se radi u dvije faze. U prvoj se identificiraju sustavi, strukture i komponente koje podliježu programu AMP. U drugoj fazi se radi evaluacija prema uvjetima okoliša, svojstvima materijala i učincima starenja.

1 INTRODUCTION

According to the data of the International Atomic Energy Agency, at the beginning of 2009, there was a total of 436 nuclear reactors operating throughout the world. The majority of those reactors started operating in the 1970s and most of them were engineered for the lifespan of 30 to 40 years.

Those power plants are nearing their initially prescribed lifespan but operating well and competitively at the same time. Therefore, extensive interest exists for the extension of their exploitation lifespan. The reasons are primarily economic because capital costs for the extension of the lifespan of those power plants are far lower than the costs of construction of any other alternative capacities.

However, it should be ascertained whether the components, structures and power plants systems exposed to aging can meet their engineered functions even in case of extended exploitation lifespan. Equipment aging can be defined as continued, time-dependant material degradation due to operating conditions, both during normal operation and in intermittent conditions.

Redundancy and diversification are principles of engineering nuclear power plants' safety systems which ensure that even if an accidental fault occurs, at least one safety system will meet its engineered function. It is feared that, in case of additional equipment loading and due to equipment aging, a simultaneous fault in critical time might happen. Such fault, in case aging was combined with accidental environmental conditions, would be characterized as a Common Cause Failure and it might make all redundant systems unavailable. When it comes to power cables, diversity in the performance of the safety system would not be very helpful either.

The Aging Management Programme (AMP) serves to adequately manage the effects of aging of the nuclear power plant's systems, structures and components. Special attention is given to those systems and components which are not subject to regular maintenance. The aim is to identify the mechanisms and aging effects, and determine whether the degradations caused by aging are within the allowed limits in order to ensure safe power plant operation for the future period.

The AMP programme usually works in two phases. The first phase is to identify systems, structures and components which are subject to the AMP programme. In the second phase, evaluation is done according to environmental conditions, material properties and aging effects.

The article describes cable aging effects in the nuc-

U članku su opisani učinci starenja kabela u nuklearnoj elektrani uzrokovani prvenstveno povišenim temperaturama i ionizirajućim zračenjem. Kao primjer naveden je program AMP u nuklearnoj elektrani Krško.

2 KLASIFIKACIJA KABELA

2.1 Kabeli u nuklearnim elektranama

Kabeli su vitalna komponenta nuklearnih elektrana (NE) jer osiguravaju napajanje električne opreme i povezuju dijelove sustava s mjernim instrumentima i opremom za nadgledanje i upravljanje pogonom elektrane. Najveći dio položenih električnih kabela može se grupirati prema općim kategorijama:

- srednjonaponski energetski kabeli,
- niskonaponski energetski kabeli,
- signalni i upravljački kabeli,
- instrumentacijski kabeli,
- telekomunikacijski kabeli,
- uzemljivački kabeli.

lear power plant caused primarily by increased temperatures and ionising radiation. The AMP programme at the Krško nuclear power plant is stated as an example.

2 CABLE CLASSIFICATION

2.1 Cables in nuclear power plants

Cables are vital components of nuclear power plants because they ensure the supply of electrical equipment and link parts of the system with measurement instruments and the equipment for the supervision and management of the power plant drive. The majority of installed power cables can be grouped according to the general categories:

- middle-voltage power cables,
- low-voltage power cables,
- signal and control cables,
- instrumentation cables
- telecommunication cables,
- grounding cables.

Tablica 1 – Relativna distribucija strujnih krugova u NE
Table 1 - Relative distribution of circuitry at the nuclear power plant

Električni krug / Circuit	Procijenjeni broj strujnih krugova / Estimated number of circuits	Udio / Share, %
Instrumentacija / Instrumentation	1 0180	20
Upravljanje / Control	3 1500	61
AC napajanje / AC supply	6 580	13
DC napajanje / DC supply	530	1
Komunikacija / Communication	2 560	5
Ukupno / Total	5 1350	100

U tablici 1 prikazana je relativna distribucija strujnih krugova nuklearne elektrane. Kako se vidi iz tablice, najveći udio čine upravljački i instrumentacijski kabeli (80 %) koji su od presudne važnosti za sigurni rad elektrane, a čije se karakteristike preklapaju s karakteristikama niskonaponskih energetskih kabela. Općenito, razmatraju se niskonaponski (< 1 kV) kabeli opterećni malim strujama, s više vodiča i plaštem. Glavna komponenta kabela su vodiči, električka izolacija i plašt. Druge komponente mogu biti različite trake (dodatna električna i mehanička zaštita ili zaštita od požara te trake za grupiranje vodiča) ili različiti materijali za punjenje kojima se poboljšavaju mehanička svojstva kabela.

Pokazalo se da starenje kabela ovisi o starenju električne izolacije, stoga je predmet interesa osnovna električna izolacija. Plašt se ne smatra

Table 1 shows the relative distribution of circuitry at the nuclear power plant:as can be read from the Table, the largest share is made up of control and instrumentation cables (80 %) which are of crucial importance for the power plant's safe operation and which properties overlap with the properties of low-voltage power cables. Generally, low-voltage (< 1 kV) cables are loaded with small currents, with several conductors and a sheet. The main components of the cable are conductors, electrical isolation and the sheet. The other components can be various bands (additional electrical and mechanical protection or fire protection and bands for conductor grouping) or different stuffing materials which enhance cables' mechanical properties.

Cable aging appears to depend on the aging of electrical isolation, so the issue of interest is basic electrical isolation. The sheet is not considered predmetom programa upravljanja starenjem, jer se smatra da je on fizička zaštita osnovne izolacije, iako nam stanje plašta kabela zapravo može poslužiti kao indikator stanja osnovne izolacije. Tim više, jer je plašt kabela obično napravljen od materijala koji ima nešto slabija svojstva od osnovne izolacije, pa su na njemu prije vidljivi negativni utjecaji okoline (ako postoje). Izolacija i plašt napravljeni su od materijala koji se baziraju na polimerima s različitim dodacima kojima se poboljšavaju mehanička, električna svojstva te otpornost na gorenje/požar. Najčešće korišteni izolacijski materijali su engl. cross-linked polyethylene – XLPE (36 %), engl. Ethylene Propylene Based Elastomers – EPR/EPDM (36 %) i engl. *polyvinyl chloride*; polivinil klorid – PVC (najčešće u starijim elektranama). Za plašt se najčešće upotrebljava engl. *chlorosulphonated polyethylene* – CDSP (poznat i kao Hypalon®). Ostali izolacijski materijali koriste se značajno manje, često za posebne primjene koje zahtijevaju specifična svojstva (na primjer, engl. *polyether ether ketone* – PEEK; koristi se u uvjetima visoke radijacije). U novijim elektranama pokazuje se trend prelaska na materijale bez halogena zbog emisija u slučaju požara.

2.2 Kabeli obuhvaćeni programom upravljanja životnim vijekom AMP (engl. *Aging management programme*)

U nuklearnoj elektrani je instalirano mnogo različitih kabela s ukupnom dužinom koja prelazi 1 000 km. Zbog te količine, potrebno je kategorizirati prema važnosti kabele uključene u proces upravljanja starenjem, stoga se navode tri pristupa identifikacije i grupa važnosti kabela:

- uključiti sve kabele iz svih sustava. Ovo je najbrža metoda identifikacije, ali u fazi primjene dovodi do bespotrebnog korištenja resursa s obzirom da se većina kabela nalazi u takvim uvjetima koji neće dovesti do takvog starenja kabela da on izgubi svoju osnovnu funkciju. Također, nisu svi kabeli važni za sigurni rad elektrane,
- isključiti pojedine sustave iz opsega programa. U slučaju ove metode, isključe se neki sustavi za koje smo sigurni da nemaju opremu i kabele važne za siguran rad elektrane. Tako se odrede svi kabeli koji su važni za siguran rad, a imamo i dio kabela koji ne bi trebali biti na našem popisu, ali se zbog pojednostavljivanja u procesu identifikacije oni tu nalaze,
- potpuna identifikacija kabela važnih za siguran rad elektrane. Ovom metodom se dobije točan popis kabela koji su ugroženi, ali je identifikacija tih kabela dugotrajna i često nisu dostupni svi potrebni podaci za ovakav pristup.

the subject of the Aging Management Programme because it is considered to be the physical protection of the basic isolation although the condition of the cable sheet can actually serve as an indicator of the condition of the basic isolation. All the more so because the cable sheet is usually made of materials of somewhat weaker properties than the basic isolation so it will show negative environmental influences (if such exist) sooner. The isolation and the sheet is made of materials based on polymers with various additives which enhance the mechanical and electrical properties and the resistance to burning/fire. The isolation materials which are used most often are the cross-linked polyethylene - XLPE (36 %), Ethylene Propylene Based Elastomers – EPR/EPDM (36 %) and polyvinyl chloride - PVC (most often in old power plants). The sheet is usually made of chlorosulphonated polyethylene – CDSP (also known as Hypalon®). Other isolation materials are used much less, often for special applications which require specific properties (for example, polyether ether ketone - PEEK; used in high-radiation conditions). Newer power plants reveal the trend of transition to halogen-free materials because of the emissions in case of fire.

2.2 Cables encompassed by the Aging Management Programme (AMP)

Many different cables are installed at the nuclear power plant and their total length exceeds 1 000 km. Because of that quantity, the cables included in the aging management process should be categorized according to their significance and therefore three identification approaches and cable significance groups are stated:

- include all the cables from all the systems. This is the fastest identification method but, in the preparatory phase, it leads to an unnecessary exploitation of resources considering the fact that most of the cables are located in such conditions which will not lead to such cable aging that would make it lose its basic function. Moreover, not all cables are important for safe operation of a power plant,
- exclude certain systems from the programme scope. In case this method is used, certain systems which surely do not have the equipment and the cables necessary for the safe operation of the power plant are turned off. In such a way, all safe-related cables are determined and we have a part of the cables which should not be on our list but are so in order to simplify the identification process,
- full identification of cables important for safe operation of the power plant. This method yields an accurate list of endangered cables, but the identification of those cables is lasting and all data necessary for this approach are not always available.

Obično se koristi druga metoda jer je ekonomski najprihvatljivija i za identifikaciju i za kasniju primjenu programa.

Kabeli izloženi težim uvjetima okoliša (visoka temperatura i radijacija) stare brže. Takvi su uvjeti u reaktorskoj zgradi. Unutar reaktorske zgrade, neki kabeli imaju veću važnost u odnosu na druge. Nakon što se kabeli u reaktorskoj zgradi rangiraju prema kriteriju sigurnosti, potrebno je procijeniti težinu uvjeta okoliša. Treba napomenuti da kabeli koji se već nalaze na EQ (engl. *Equipment/ Environmental Qualification* – EQ) listi (lista opreme koja je predmet procesa kvalifikacije za uvjete okoline kako to zahtjeva regulativa) ne ulaze u opseg programa starenja kabela. Za njih vrijede druga, stroža pravila, jer ti kabeli moraju do kraja životne dobi elektrane još izdržati i uvjete u slučaju akcidentalnog događaja (starenje je implicitno uključeno u EQ proces). Nakon toga, identificiraju se kabeli izvan reaktorske zgrade koji su izloženi teškim uvjetima okoliša i stoga ih je potrebno ocijeniti i pratiti njihovo stanje.

Za praćenje starenja kabela najvažnije je poznavanje uvjeta okoliša koji mogu ubrzati starenje (učinci na organske materijale koji se koriste kao izolacija). Dominantni faktori na starenje tijekom normalnog rada nuklearne elektrane su temperatura i doza zračenja (u nekim posebnim slučajevima, vlažnost ili kemijsko zagađenje mogu biti važni) stoga je korisno pratiti njihove vrijednosti unutar reaktorske zgrade. Ukoliko ti podaci nisu dostupni, mogu se koristiti podaci iz projektne dokumentacije.

Identifikacija kritičnih mjesta (engl. *hot spots*; mjerene vrijednosti temperature, radijacije, vlage, kemijskih uvjeta i /ili vibracija su značajno više nego prosječne vrijednosti šireg područja) je vrlo važna. Ti uvjeti će najvjerojatnije uzrokovati degradaciju kabela tijekom životnog vijeka elektrane.

Na slici 1 prikazan je proces identifikacije i dodjeljivanje prioriteta kabelima po fazama.

U svakoj fazi vrši se procjena kojom se smanjuje broj kabela čije se starenje ocjenjuje i prati.

U prvoj fazi identificira se tip strujnoj kruga/sustava kojem kabel pripada. Svi kabeli koji su važni za sigurnost ulaze u procjenu u sljedećoj fazi. Svim ostalim kabelima dodjeljuje se nizak prioritet za upravljanje starenjem. Može se, također, odlučiti da u drugu fazu uđu i određeni pomoćni kabeli važni za rad elektrane.

Druga faza identificira normalne pogonske uvjete (npr. temperatura, zračenje) kabela tijekom životnog vijeka elektrane, ne uključujući i uvjete akcidentnih događaja. Osim tih, identificiraju se i uvjeti

The second method is used more often because it is economically most acceptable both for the identification and subsequent application of the programme.

Cables exposed to more adverse environmental conditions (high temperature and radiation) age more quickly. Such are the conditions in the reactor building. Within the reactor building, some cables are more important than the others. After the cables in the reactor building are sorted according to the safety criteria, it is necessary to estimate the adverseness of the environmental conditions. It should be mentioned that the cables already found on the EQ Equipment/Environmental Qualification List (the list of equipment which is the object of the qualification process for the environmental conditions as required by the regulations) are not included in the scope of the cable aging programme. These are subject to other, stricter rules, because until the end of the power plant's lifespan, these cables still have to endure the conditions in case of accidental event as well (aging is implied in the EQ process). After that, cables outside the reactor building exposed to adverse environmental conditions are identified and therefore need to be evaluated and their condition monitored.

The monitoring of the cables primarily requires the awareness of the environmental conditions which might speed up the aging (effects on organic materials used as isolation). Dominant factors affecting aging during normal power plant operation are temperature and radiation dosage (in some special cases, moisture or chemical pollution might be important) so it is useful to monitor their values within the reactor building. If these data are not available, data from the project documentation can be used.

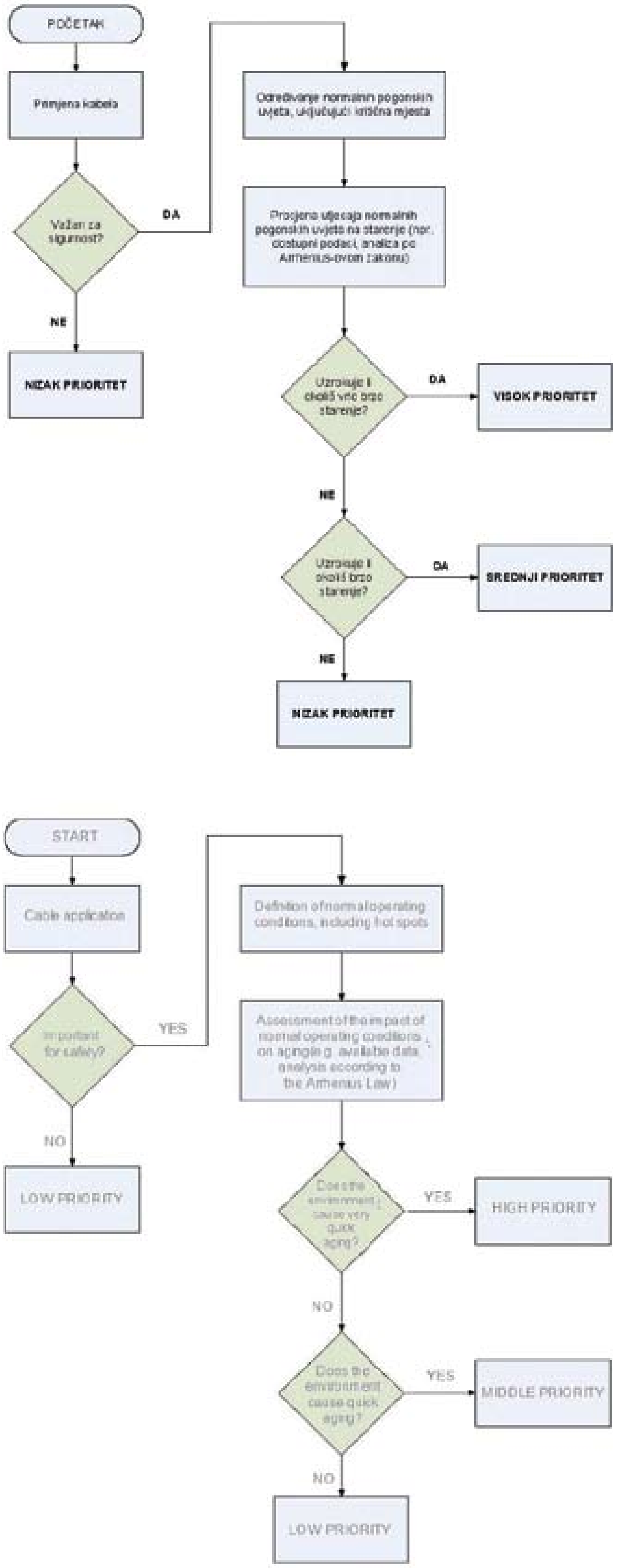
Identification of hot spots (measured values of temperature, radiation, moisture, chemical conditions and/or vibrations are significantly higher than average values of the wider area) is very important. Those conditions will most probably cause degradation of cables during the power plant's lifespan.

Figure 1 shows the process of identification and attribution of priorities to cables according to phases.

In each phase, assessment which reduces the number of cables the aging of which is being assessed and monitored is carried out.

In the first phase, the type of circuitry/system which the cable belongs to is identified. All the safety-related cables are included in the assessment in the next phase. All the other cables are attributed low priority in the aging management. It can also be decided for the second phase to include certain auxiliary cables necessary for the power plant's operation as well.

The second phase identifies normal cable operating conditions (e.g. temperature, radiation) during the



Slika 1 — Proces identifikacije kabela važnih za sigurnost
Figure 1 — Process of identification of safety-related cables

na kritičnim mjestima. Koriste se mjerene vrijednosti, a u slučaju da one nisu dostupne, koriste se podaci iz projektne dokumentacije.

Nakon što su identificirani pogonski uvjeti, u trećoj fazi procjenjuje se njihovo djelovanje na starenje kabela te se dodjeljuju prioriteti:

- **visok prioritet** – kabeli važni za sigurnost instalirani u prostorima čiji uvjeti okoliša mogu uzrokovati ozbiljno starenje tijekom životnog vijeka NE,
- **srednji prioritet** – kabeli važni za sigurnost instalirani u prostorima čiji uvjeti okoliša mogu uzrokovati umjereno starenje tijekom životnog vijeka NE,
- **nizak prioritet** – kabeli važni za sigurnost instalirani u prostorima čiji uvjeti okoliša mogu uzrokovati minorno starenje tijekom životnog vijeka NE.

Evaluacijski proces se može pročistiti i dopuniti novim informacijama. Ukoliko se, na primjer, praćenjem visokorizičnih kabela pokaže da je degradacija manja od očekivane, kabel se može spustiti u grupu niže rizične skupine. Isto tako, ukoliko novije istraživanje pokaže ozbiljniji utjecaj okoliša na starenje kabela, kabel se može smjestiti u grupu više rizičnih kabela.

Očekuje se podvrgavanje kabela iz grupe najvišeg prioriteta daljnjim aktivnostima iz procesa upravljanja starenjem kabela.

3 STARENJE KABELA

Starenje kabela je kemijski (kidanje i/ili umrežavanje polimerskih lanaca, oksidacija, difuzija kisika) ili fizikalni proces (isparavanje i/ili migracija plastifikatora) na molekularnoj razini materijala koji se očituje u nepovratnim promjenama u električkim i mehaničkim svojstvima materijala. Te promjene uključuju smanjenje elastičnosti, povećanje tvrdoće plašta i promjene u električkim svojstvima.

Starenje kabela ovisi o materijalu (sastavu polimera), skladištenju prije instalacije, normalnim pogonskim uvjetima i vremenu. Različite karakteristike okoliša (npr. temperatura, ionizirajuće zračenje, prisustvo kisika i vodene pare) i određeni mehanički uvjeti (npr. vibracije) mogu značajno utjecati na brzinu starenja. Među tim uzrocima starenja, najznačajniji su temperatura i zračenje.

Starenje kabela ovisno o temperaturi može biti opisano Arrheniusovim modelom. U Arrheniusovom modelu brzina reakcija R je opisana prema relaciji:

power plant's lifespan, not including accidental event conditions. Besides those, conditions in hot spots are also identified. Measured values are used, and, in case these are not available, data from the project documentation are used.

After the operative conditions have been defined, in the third phase, their effect on cable aging is assessed and priorities are attributed.

- **high priority** - safety-related cables installed in the spaces which environmental conditions can cause serious aging during the nuclear power plant's life span,
- **middle priority** - safety-related cables installed in the spaces which environmental conditions can cause moderate aging during the nuclear power plant's life span,
- **low priority** - safety-related cables installed in the spaces which environmental conditions can cause minor aging during the nuclear power plant's life span,

The evaluation process can be refined and supplemented with new information. If, for example, the monitoring of high-risk cables reveals that the degradation is lower than expected, the cable can be demoted to the low-risk group. Moreover, if recent research shows serious environmental impact on cable aging, the cable can be placed in the higher-risk cables group.

Subjecting the cables from the top priority group to further activities from the cable aging management process is expected to take place.

3 CABLE AGING

Cable aging is a chemical (breaking and/or networking of polymer chains, oxidation, oxygen diffusion) or physical process (evaporation and/or migration of the plasticizer) at the material's molecular level which is evidenced by irreversible changes in the material's electrical and mechanical properties. Those changes include reduced elasticity, increased sheet stiffness and changes in electrical properties.

Cable aging depends on the material (polymer composition), storage before installation, normal operating conditions and time. Various environmental properties (e.g. temperature, ionising radiation, presence of oxygen and water vapour) and certain mechanical conditions (e.g. vibrations) can significantly affect the aging rate. The most important among those aging agents are temperature and radiation.

Temperature-dependant cable aging can be described by virtue of the Arrhenius model. In the Arrhenius model, reaction rate R is described according to the relation:

$$R = C\,\mathrm{e}^{\frac{-E_\mathrm{a}}{kT}}\ , \qquad (1)$$

gdje je:

C – konstanta,
k – konstanta,
E_a, J/mol – aktivacijska energija za proces,
T, K – apsolutna temperatura.

Promatrajući pokus ubrzanog termičkog starenja kroz širok temperaturni spektar, ponekad se pojavljuje točka loma koja se podudara s promjenom kinetičkog režima. Vrijednost aktivacijske energije nije konstantna u cijelom temperaturnom rasponu. U većini takvih primjera uočeno je da su vrijednosti E_a niže pri nižim temperaturama. U tim uvjetima, ekstrapolacija podataka dobivenih mjerenjem pri višim temperaturama može značajno podcijeniti starenje pri nižim temperaturama. Zato se preporuča da porast temperatura u pokusu ubrzanog starenja ne bude viši od 25 °C. Vrijednost aktivacijske energije važna je za rezultate, a za upute o primjeni Arrhenius-ovog zakona koristi se IEC 216 [2].

Za primjenu na ubrzanom termičkom starenju prikladan je ovaj oblik Arrheniusova modela:

where it is as follows:

C – constant,
k – constant,
E_a, J/mol – activation energy for the process,
T, K – absolute temperature.

In observing the experiment of accelerated thermal aging through a wide temperature spectre, sometimes a breakpoint occurs which coincides with the change of kinetic regime. The value of energy activation is not constant in the entire temperature range. In most of such cases, it has been noticed that the values E_a are lower at lower temperatures. In those conditions, extrapolation of data obtained by measurement at higher temperatures can significantly underestimate aging at lower temperatures. That is why it is recommended that increased temperature in the accelerated aging process does not exceed 25 °C. The value of activation energy is important for the results, and the IEC 216 [2] is used for the instructions on the application of the Arrhenius model.

This form of the Arrhenius model is suitable for application on accelerated thermal aging.

$$t_\mathrm{s} \cdot t_\mathrm{a}^{-1} = \mathrm{e}^{E_\mathrm{a} \cdot k^{-1} \cdot \left(T_\mathrm{s}^{-1} - T_\mathrm{a}^{-1}\right)}\ , \qquad (1)$$

gdje je:

E_a, J/mol – aktivacijska energija,
k – Boltzmanova konstanta,
t_a – vrijeme ubrzanog starenja na temperaturi T_a,
t_s – vrijeme pogona koje se simulira na nekoj temperaturi T_s nakon kojeg se postiže degradacija.

Osim vanjskog utjecaja temperature, zagrijavanju izolacije kabela može pridonijeti i ohmsko zagrijavanje samog vodiča. Naravno, ovaj utjecaj se razmatra samo u slučaju energetskih kabela i to kod onih koji su opterećeni više od 80 % vremena.

where it is as follows:

E_a, J/mol – activation energy,
k – Boltzman constant,
t_a – accelerated aging time at the temperature T_a,
t_s – time of operation simulated at a certain temperature T_s after which degradation is achieved.

Besides the outer temperature impact, Ohm's heating of the cable itself can also contribute to the warming of the cable isolation. Of course, this impact is analysed only in case of power cables and that being those which are loaded more than 80 % of the time.

4 UPRAVLJANJE STARENJEM KABELA KROZ KVALIFIKACIJU ZA UVJETE OKOLIŠA

Upravljanje starenjem kabela osigurava njihovo ispravno funkcioniranje tijekom životnog vijeka

4 CABLE AGING MANAGEMENT THROUGH ENVIRONMENTAL QUALIFICATION TESTS

Cable aging management ensures their proper functioning during the life span of the nuclear power

NE. Kroz kvalifikaciju za uvjete okoliša garantira se ispravan rad kabela pod specifičnim uvjetima, kako u normalnim pogonskim uvjetima tako i u akcidentnim uvjetima.

Inicijalna kvalifikacija (engl. *type testing*) koristi se za utvrđivanje uvjeta okoliša novog kabela prije instalacije. Osnovni cilj inicijalne kvalifikacije je dokaz da je kabel kvalificiran za određene uvjete (normalne i abnormalne) i definira granice primjene. Također, definira kvalificiran životni vijek kabela. Alternativni pristup je uspostavljanje kvalificiranih uvjeta.

Kvalificirani životni vijek je vremenski period u kojem, pod normalnim uvjetima, starenje ne utječe negativno na rad (kabela, opreme) u kasnijim uvjetima eventualnih akcidentalnih događaja [2].

Kvalificirani uvjeti su uvjeti okoliša/pogona koji se izražavaju kroz mjerljive indikatore za koje je dokazano da ne utječu negativno na rad (kabela, opreme) [2].

Kvalifikacija za uvjete okoliša postiže se prikladnom kombinacijom inicijalne kvalifikacije, primjenom stečenih iskustava u sličnim primjenama te rezultatima analize (ekstrapolacija inženjerskih podataka i pogonskog iskustva).

Testovi za kvalifikaciju za uvjete okoliša uključuju funkcionalna ispitivanja, simulaciju ubrzanog starenja (uključujući procjenu dugotrajnog rada) i testiranje rada pri akcidentalnim i post-akcidentalnim uvjetima.

Termičko starenje kabela u nuklearnoj elektrani je uvijek prisutno u nekoj mjeri. Ubrzano termičko starenje postiže se izlaganjem kabela znatno višim temperaturama od onih kojima je izložen u normalnim pogonskim uvjetima (pretpostavlja se primjenjivost Arrheniusovog zakona).

Na određivanje kvalificiranog životnog vijeka utječe [2]:

- temperatura radnog okoliša – manja sigurnosna granica je potrebna ukoliko je temperatura okoliša kontrolirana,
- svojstva izolatorskog materijala – mjerenje aktivacijske energije u određenom temperaturnom intervalu,
- tolerancija testa,
- količina uzoraka.

Ubrzano radijacijsko starenje znači izlaganje kabela dozi zračenja koju bi skupio u cijelom očekivanom životnom vijeku (bez akcidentnih uvjeta) u kratkom vremenu. Ta doza je mnogo viša od radijacijske doze u normalnim pogonskim uvjetima i zapravo ne prikazuje realne uvjete. U literaturi [7]

plant. By virtue of environmental qualification testing, proper cable functioning is guaranteed under specific conditions, both in normal operating conditions and in accidental conditions.

Initial type testing is used for defining environmental conditions of the new cable before installation. The basic aim of the initial qualification is proving that the cable qualifies for certain conditions (normal and abnormal) and it defines application limits. Moreover, it defines the cable's qualified life span. Establishment of qualified conditions is the alternative approach.

Qualified life span is the temporal period in which, under normal conditions, aging does not negatively affect the operation (of cables, equipment) in subsequent conditions of possible accidental events [2].

Qualified conditions are environmental/operating conditions which are expressed through measurable indicators for which it has been proven that they negatively affect the operation (of cables, equipment) [2].

Environmental qualification is achieved by the right combination of initial qualification, application of acquired experiences in similar applications and analysis results (extrapolation of engineering data and operating experience).

Environmental qualification tests include functional testing, simulation of accelerated aging (including the estimate of lasting operation) and testing the operation in accidental and post-accidental conditions.
Thermal cable aging in the nuclear power plant is always present to a certain extent. Accelerated thermal aging is achieved by exposing the cable to significantly higher temperatures than those to which it is exposed in normal operating conditions (the applicability of the Arrhenius law is assumed).

The definition of qualified life span depends on [2]:

- working environment temperature – a lower safety limit is required if the environment temperature is controlled,
- isolation material properties – measuring the activation energy in a certain temperature interval,
- test tolerance,
- number of samples.

Accelerated radiation aging implies the cable's exposure to radiation dosages which it would normally collect throughout the entire expected life span (without accidental conditions) in a short period of time. That dosage is significantly higher than the radiation dosage in normal operating conditions and actually does not indicate realistic conditions. Literature [7] describes accelerated radiation aging and the results reveal that there is a cut-off value of the radiatiopisano je ubrzano radijacijsko starenje i rezultati pokazuju da postoji granična vrijednost radijacijske doze izloženosti ispod koje je utjecaj radijacije na starenje beznačajan i može se zanemariti. Također, rezultati su pokazali da je ta granična vrijednost viša nego se očekivalo.

Kao i u slučaju termičkog starenja, na rezultat utječu doza radijacije u normalnim pogonskim uvjetima, učinak radijacije na izolacijski materijal kabela, tolerancije testa i količina uzoraka.
Kabeli najčešće nisu izloženi uvjetima velike vlažnosti. Velika vlažnost ubrzava termičko starenje kabela jer hidroliza pridonosi degradaciji izolacijskog materijala (ova pojava se manifestira samo u slučaju srednjonaponskih kabela, dok je u slučaju niskonaponskih zanemariva).

Također, kabeli najčešće nisu izloženi značajnim vibracijama. Ukoliko jesu, mogu se pojaviti izuzetno male pukotine koje doprinose starenju. Ovdje treba napomenuti da su kabeli kojima se često manipulira (spajanje i odspajanje opreme za vrijeme remonta, kalibracije opreme) također vrlo podložni oštećenjima i ubrzanom starenju.

Za testiranje akcidentalnih uvjeta koriste se različiti predviđeni događaji (engl. *Design Basis Event* – DBE) koje obično karakteriziraju visoka doza radijacije praćena velikom količinom oslobođene topline. Najčešće se koristi LOCA (engl. *Loss of Coolant Accident*; akcident gubitka rashladnog sredstva) kao najgori scenarij.

Test se izvodi u dva koraka. Radijacijski test se odvija u uvjetima doza radijacije od $1 \mathrm{kGy/h}$ i $10 \mathrm{kGy/h}$ i temperatura značajno viših od temperatura normalnog pogona kako bi se uzelo u obzir zagrijavanje uzrokovano prolaskom struje (iako to zapravo nije relevantno za instrumentacijske kabele). Termodinamički test je projektiran prema posebnostima nuklearne elektrane i uključuje odnos temperature/tlaka pare kao funkciju vremena prema uvjetima predviđenih akcidentnim događajem. Ovo testiranje se vrši samo na EQ kabelima (engl. Eqipment/Enviromental/ Qualification EQ – kvalifikacija za uvjete okoline). Za ostale kabele pretpostavljaju se normalni radni uvjeti (akcidentni događaji ne spadaju u normalne radne uvjete).

Kvalifikacija uvjeta okoliša primarno identificira starenje kabela važnih za sigurnost. Dodatne aktivnosti (praćenje uvjeta okoliša, praćenje starenja kabela, dodatni testovi ubrzanog starenja kabela) služe za dokazivanje graničnih uvjeta primjene i potvrđivanje kvalificiranog životnog vijeka kabela. Održavanje (praćenje i upravljanje) uvjeta okoliša pridonosi kontroli starenja, točnijoj procjeni kvalificiranog životnog vijeka kabela, a time i općenito sigurnosti elektrana.

on exposure dosage under which the radiation effect on aging is insignificant and can be disregarded. Moreover, the results have shown that the cut-off value is higher than expected.

Just as in the case of thermal aging, the result also depends on the radiation dosage in normal operating conditions, radiation impact on the cable's isolation material, test tolerances and sample quantity.

Cables are usually not exposed to high-moisture conditions. High moisture speeds up the cable's thermal aging because the hydrolysis contributes to the degradation of the isolation material (this only occurs in case of middle-voltage cables, while it is insignificant in case of low-voltage cables).

Furthermore, cables most often are not exposed to significant levels of vibration. If they are, extremely small ruptures can appear which contribute to aging. It should be mentioned here that the cables which are manipulated often (connection and disconnection of the equipment during repair or equipment calibration) are also very prone to damages and accelerated aging.

Various Design Basis Events (DBE) are used for the testing of accidental conditions and these are often characterized by high dosage of radiation accompanied with high levels of released heat. The Loss of Coolant Accident (LOCA) is most often used as the worst-case scenario.

The test is performed in two steps. The radiation test takes place in the conditions of radiation dosage between $1 \mathrm{kGy/h}$ and $10 \mathrm{kGy/h}$ and temperatures significantly higher than normal operating temperatures so as to take into consideration the heating caused by passage of current (although that actually is not relevant for instrumentation cables). The thermodynamic test is designed according to the specificities of the nuclear power plant and it includes the relation temperature/vapour pressure as the function of time according to the conditions predicted by the accidental event. This testing is performed on EQ cables only. Eqipment/Enviromental/ Qualification EQ. Normal operating conditions are assumed for the other cables (accidental conditions do not fall under normal operating conditions).

Environmental qualification primarily identifies the aging of those cables which are important for safety. Additional activities (monitoring environmental conditions, monitoring cable aging, additional accelerated cable aging tests) are used to prove cut-off application conditions and confirm the cable's qualified life span. Maintenance (monitoring and management) of environmental conditions contributes to aging control, more accurate estimate of the cable's qualified life span, and thus generally to the safe operation of power plants.

5 PROGRAM AMP U NUKLEARNOJ ELEKTRANI KRŠKO

Kao dio programa PSR (engl. *Periodic Safety Review*; redovno izvješće o sigurnosti) u nuklearnoj elektrani Krško je rađen program AMP. AMP je program koji osigurava praćenje starenja sve pasivne opreme za koju nije predviđena preventivna zamjena ili nije definirana kvalificirana životna dob. Program se provodi u skladu s GALL programom (engl. *Generic Aging Lessons Learned*) [11] američke nuklearne regulatorne agencije (engl. *Nuclear Regulatory Commission* – NRC). U NEK-u je, u sklopu priprema za dobivanje dozvola za produljenje životnog vijeka elektrane, početkom 2009. godine završen AMP. Cilj AMP-a je na sustavan način analizirati učinke i utjecaje starenja. Potrebno je zaključiti da li se degradacije izazvane učincima starenja u elektrani kontroliraju na način da je granica sigurnosti sačuvana.

Program AMP, nakon što se uvede, trajno se održava i služi kao osnova za moguće produljenje životnog vijeka nuklearne elektrane. Regulatorna osnova je US NRC 10CFR Part 54 – Requirements for Renewal of Operating licenses for Nuclear Power Plant.

U sklopu programa provedena je analiza tipova kabela, materijala od kojih je izrađena kabelska izolacija, te uvjeta okoline (temperatura, zračenje, vlaga) u kojima se kabeli nalaze. Zaključeno je da je stanje kabela na vrlo zadovoljavajućoj razini. Najvažniji razlog, zaslužan za to, jest činjenica da po tehničkim specifikacijama za kabele bitne za sigurnost (engl. Safety Related – SR), materijali izolacije smiju biti samo EPR ili XLPE ili materijali koji imaju bolja svojstva od njih. Osim ovih materijala, pronađeni su još i HTK (engl. High Temperature Kerite, koji je ustvari proizvođačko ime za EPR) i Teflon (za uvjete visokih temperatura). Vidljivo je da nisu korišteni PVC kabeli s kojima starije nuklearne elektrane imaju problema, jer su parametri za 60-godišnji vijek trajanja kabela puno lošiji nego za materijale koji su korišteni u NEK. Još je pronađen i CSPE, ali on je korišten samo kao plašt. CSPE ima nešto lošije granične parametre od osnovne izolacije koja je korištena. Ova činjenica je ustvari i povoljna, kao što je već napomenuto, jer običnom vizualnom inspekcijom može se provjeriti stanje kabela i, ako je plašt u dobrom stanju, znači da je i osnovna izolacija uredu. Naravno, neispravnost plašta je indikator za dodatne testove osnovne izolacije.

Za lakšu procjenu stanja kabela postoje tablice s graničnim vrijednostima temperature i zrače-

5 AMP PROGRAMME AT THE KRŠKO NUCLEAR POWER PLANT

As part of the PSR (Periodic Safety Review) Programme, the AMP programme was undertaken at the Krško nuclear power plant. AMP is a programme which ensures aging monitoring of all the passive equipment for which preventive alternative has not been planned or for which the qualified lifespan has not been defined. The programme is being managed in compliance with the GALL (Generic Aging Lessons Learned) programme [11] of the American Nuclear Regulatory Commission (NRC). Within the scope of the preparations for obtaining permits for extending the power plant's lifespan, at the beginning of 2009, the AMP was completed. The objective of the AMP is to systematically analyse the effects and impacts of aging. The conclusion should be drawn whether the degradations caused by aging effects are controlled at the power plant in such a manner that the safety limit remains preserved.

The AMP programme, after being implemented, is permanently maintained and serves as a basis for possible extension of the nuclear power plant's life span. The regulatory basis is US NRC 10CFR Part 54 – Requirements for Renewal of Operating Licenses for Nuclear Power Plants.

Analysis of cable types, materials from which cable isolation was made and environmental conditions (temperature, radiation, moisture) in which cables are located was carried out within the programme. The conclusion was made that cable condition was at a very satisfactory level. The most important reason responsible for this is the fact that, according to technical specifications for safety related (SR) cables, isolation materials must only be EPR or XLPE or materials with better propertiesBesides the new materials, High Temperature Kerite (HTK), which is actually the production name for EPR and Teflon (for high temperature conditions) were found as wellPVC cables, which create problems for older nuclear power plants, evidently were not used because the parameters for the 60-year life span are much worse than for the materials which are used in the nuclear power plant. CSPE was also found but it was only used as the sheet. CSPE has somewhat lower cut-off parameters than the basic isolation which was used. As already mentioned, this fact is actually favourable as well because regular visual inspection can provide information on the cable condition and, if the sheet is in good condition, it also means that the isolation is good. Of course, sheet faultiness is an indicator for additional tests of the basic isolation.

For easier assessment of the cable's condition, tables exist which include cut-off values of temperature and nja za 60-godišnji vijek trajanja kabela iz kojih se može brzo procijeniti (ako znamo materijal i uvjete okoline u kojem se nalazi) stanje kabela. Npr. za XLPE kabel maksimalna konstantna temperatura pri kojoj izolacija traje 60 godina je 86,6 °C, a zračenje $1x10^6$ Gy, za EPR/EDP kabele temperatura je 75,0 °C i zračenje $5x10^5$ Gy, za HTK – N98 kabel 85,2 °C i $1x10^6$ Gy, FEP (engl. *Florinated ethylene propylene*, teflon) 34,17 °C i $5x10^2$ Gy, CSPE kabel 75,0 °C i $2x10^4$ Gy i za PVC kabele vrijednosti temperature i radijacije su 44,2 °C i $2x10^5$ Gy.

Naravno da su rijetki prostori s konstantnom temperaturom (postoji barem razlika u temperaturi zbog godišnjih doba) pa je potrebno i to uzeti u obzir, ako se kabeli nalaze u uvjetima blizu graničnih vrijednosti. Za kvalitetnu procjenu uvjeta potrebno je pratiti parametre okoline barem godinu dana i onda se može odrediti neka srednja vrijednost tih parametara.

6 METODE PRAĆENJA STARENJA KABELA

Praćenje starenja kabela su aktivnosti koje daju informacije o indikatorima koji predstavljaju razinu degradacije. Primjer indikatora su:

- električki indikatori (otpor izolacije, rasipna struja zbog nesavršenosti izolacije (engl. *leakage current*), gubici, pad napona itd.) – nije reprezentativan indikator starenja,
- kemijska svojstva – jer starenje izravno utječe na molekularnu strukturu izolacijskog materijala, pojedina svojstava materijala izravni su indikatori razine starenja,
- mehanička svojstva – prekidna elastičnost je prihvaćeni indikator starenja, tvrdoća i svojstva tlačnih modula su također prihvaćeni indikatori starenja nekih izolacijskih materijala,
- vizualni indikatori – promjena boje (blijeđenje boje ili tamnjenje), ispucanost površine, promjene u dimenzijama su često indikatori promjene svojstava određenih materijala uslijed starenja; mogu se koristiti samo kao početni indikator koji inicira druge, pouzdanije testove.

Različite metode su do sada razvijene i testirane, ali još ima prostora za razvoj novih. Većina tih metoda daje rezultate za točno određenu točku/poziciju kabela i ne daje podatke o graničnim područjima. Mjerenja u intervalima duž kabela daju općeniti trend i ne identificiraju kritična mjesta. Isto tako, većina metoda ograničena je na plašt kabela i svojstva izolacije mogu se testirati samo na krajevima ili priključnim kutijama (ukoliko se ne mogu skupiti uzorci).

radiation for 60-year cable lifespan and from these tables the cable's condition can easily be assessed (if we know the material and its environmental conditions). For example, the maximum constant temperature, for the XLPE cable, at which the isolation endures 60 years, is 86,6 °C, and radiation $1x10^6$ Gy, for the EPR/EDP cables, the temperature is 75,0 °C and radiation is $5x10^5$ Gy, for the HTK - N98 cable it is 85,2 °C and $1x10^6$ Gy, for the FEP (Fluorinated ethylene propylene, Teflon) 34,17 °C and $5x10^2$ Gy, for the CSPE cable 75,0 °C and $2x10^4$ Gy and for the PVC cables, temperature and radiation values are 44,2 °C and $2x10^5$ Gy.

Areas with constant temperatures are, of course, rare (temperature varies at least depending on the season) so that needs to be taken into account as well if the cables are located in conditions near cut-off values. In order for the conditions to be well assessed, parameters need to be monitored for at least a year and then some mean value of those parameters can be determined.

6 CABLE AGING MONITORING METHODS

Monitoring cable aging is an activity which yields information on the indicators which represent the level of degradation. Examples of indicators are:

- electrical indicators (isolation resistance, leakage current due to the imperfections of the isolation, losses, reduced voltage, etc.) – not a representative indicator of aging,
- chemical properties – because aging directly impacts the molecular structure of the isolation material, certain material properties are direct indicators of the aging level,
- mechanical properties – elasticity modulus is an accepted aging indicator; hardness and properties of pressure module are also accepted aging indicators for some isolation materials,
- visual indicators – change of colour (colour fading or darkening), cracked surface and change of dimensions are often indicators of changed properties of certain materials due to aging; these can only be used as initial indicators which initialize other, more reliable tests.

Various methods have been developed and tested so far, but there is still space for development of new methods. Most of those methods yield results for the exactly determined cable spot/position and do not yield data on cut-off areas. Measurements in intervals along the cable yield a general trend and do not identify hot spots. Moreover, most of the methods are limited to the cable sheet and isolation properties can be tested only at the ends or terminal boxes (if samples cannot be collected).

Trenutačno najraširenije metode su mjerenje dubine otiska (engl. *Indenter Modulus – IM metoda*), mjerenje produljenja pri prekidanju (engl. *Elongation at Break* – EAB metoda) i termička analiza mikro uzoraka mjerenjem vremena (engl. *Oxidation Induction Time* – OIT) ili temperature (engl. *Oxidation Induction Temperature* – OITP) potrebnih za induciranje oksidacije. Novija LIRA (engl. *Line Resonance Analysis*) metoda daje dobre rezultate za identificiranje kritičnih mjesta. Druge poznate metode su termo-gravimetrijska analiza (TGA) koja mjeri gubitak težine uzorka pri zagrijavanju, mjerenja torzionog momenta (mjeri se krutost materijala) i mjerenja gustoće. U istraživačkim laboratorijima su testirane i neke druge metode (engl. *Fourier Transform Infrared Spectoscopy* – FTIR, foto-akustična spektroskopija, kemijska luminiscencija) koje se značajnije ne primjenjuju.

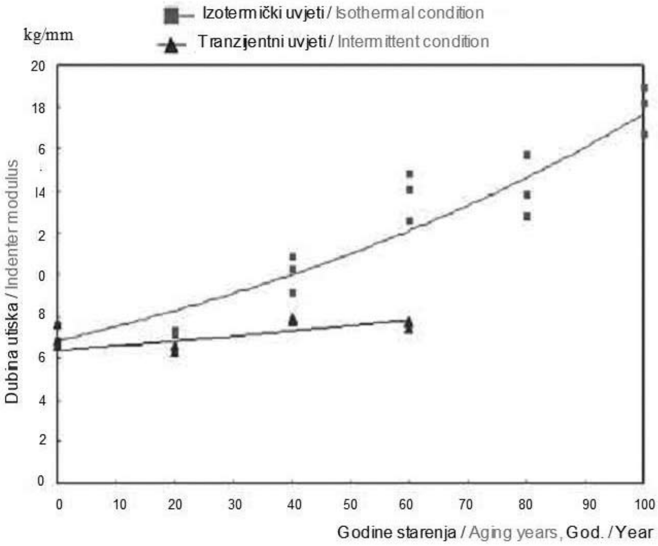
6.1 Mjerenje dubine otiska

Mjerenje dubine otiska je dobar pokazatelj starenja kabela; pokazuje kompresivnost (stlačivost) materijala pod kontroliranim uvjetima. Sonda se utiskuje u površinu materijala i mjeri se krivulja pomaka. Nagib krivulje se uzima kao vrijednost IM (engl. *Indenter Measurements*) modula. Izmjerene vrijednosti ovise o parametrima testa (brzini i sili utiskivanja sonde, temperaturi), stoga za usporedbu rezultata treba još navesti proceduru kalibriranja. Metoda pokazuje dobru korelaciju izmjerenih vrijednosti IM modula i starenja kabela.
Rezultati mjerenja IM modula opisanih u literaturi [8] prikazani su na slici 2.

Currently, the most wide-spread methods are the indenter modulus (IM) measurement method, elongation at break (EAB) measurement method and the thermal analysis of micro samples by measuring oxidation induction time (OIT) or the oxidation induction temperature (OITP). The more recent LIRA Line Resonance Analysis method, yields good results in the identification of hot spots. Other familiar methods are thermo-gravimetric analysis (TGA) which measures the sample's weight loss at warming, measurements of torque (material rigidity is measured) and measurements of density. Some other methods have also been tested in research laboratories (Fourier Transform Infrared Spectroscopy – FTIR, photo-acoustic spectroscopy, chemical luminescence) which are not applied to a significant extent.

6.1 Indenter measurement

Indenter measurement is a good indicator of cable aging; it shows material compressibility under controlled conditions. The probe is pressed into the material surface and the shift curve is measured. The curve pitch is taken as the value of the indenter measurements modulus. Measured values depend on test parameters (speed or probe impressing force, temperature), therefore, the comparison of results also requires the calibration procedure. The method shows good correlation of the measured values of the IM modulus and cable aging.
Results of the IM modulus measurement described in literature [8] are shown in Figure 2.



Slika 2 — Rezultati mjerenja IM modula
Figure 2 — Results of the IM modulus measurement

Za potrebe pokusa, simulirano je ubrzano starenje kabela zagrijavanjem. U jednom slučaju, zagrijavanje na 130 °C je kontinuirano, u drugom se periodi zagrijavanja na 130 °C izmjenjuju s periodima u kojima je temperatura 80 °C. Obje krivulje kontinuirano rastu, nema kritičnih i/ili prekidnih točaka. Nagibi krivulja su različiti (različita brzina starenja), stoga kontinuirano zagrijavanje u periodu od 60 godina daje dvostruko veće vrijednosti nego u slučaju kada se periodi zagrijavanja izmjenjuju.

Zaključak je da uzimajući u obzir redovne remonte (koji se odvijaju svakih 12 ili 18 mjeseci) kada nema opterećenja na kabel, postoji mogućnost oporavka materijala te se životni vijek nuklearne elektrane može produžiti na 60 godina.

6.2 EAB metoda

EAB metoda, odnosno mjerenje prekidne elastičnosti, smatra se pouzdanom metodom za procjenu starenja kabela. Vrijednost od 50 % apsolutne vrijednosti produljenja pri prekidu se činio kao granična vrijednost kvalificiranog životnog vijeka materijala. Kasnije studije su pokazale da rezultati nekih materijala (većinom kod PVC) znatno odstupaju, stoga IEC standard 544 preporuča 50 % početne vrijednosti kao graničnu vrijednost kriterija. Također, preporuča se korištenje dostupnih informacija o određenom materijalu za definiranje kriterija (50 % apsolutne ili 50 % relativne vrijednosti).

Rezultati mjerenja EAB metode opisanih u literatu-

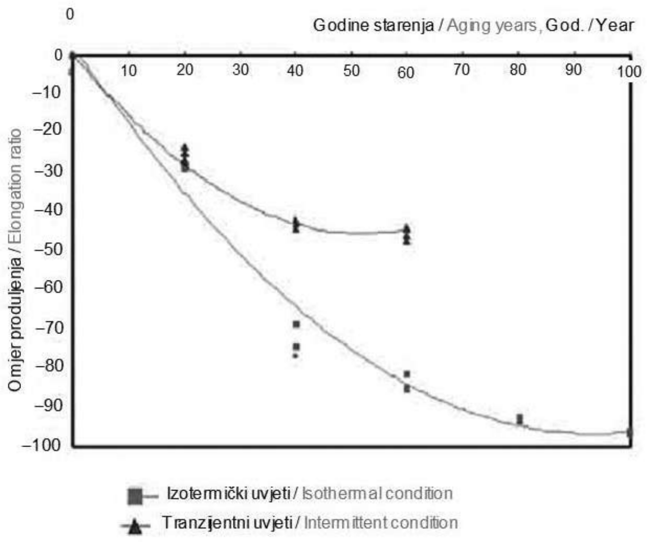
For the purpose of experiment, accelerated cable aging has been simulated by warming. In one case, warming to 130 °C was continuous and in the other, warming to 130 °C alternated with periods in which temperature was 80 °C. Both curves have been rising continuously, there were no hot spots and/or cut-off points. Curve pitches are different (different aging rate) so continuous warming in a 60-year period yields a value twice as high as in the case of intermittent warming periods.

The conclusions is that, taking into consideration regular repairs (which take place every 12 or 18 months) when the cable is not loaded, there is possibility of material recovery and the nuclear power plant's lifespan can be extended to 60 years.

6.2 EAB Method

The EAB method, that is, elasticity modulus measurement, is considered to be a reliable method for the estimate of cable aging. Value of 50 % of the absolute value of elongation at break seemed as the cut-off value of the material's qualified lifespan. Later studies showed that the results of some materials (mostly with PVC) deviate significantly, so the IEC standard recommends 50 % of initial value as the cut-off criteria value. Moreover, it is recommended to use available information on a certain material for the definition of criteria (50 % absolute or 50 % relative value).

Measurement results of the EAB method described in literature [8] are shown in Figure 3. In case of con-



Slika 3 — Rezultati EAB metode za kontinuirane i periodične uvjete starenja
Figure 3 — EAB method results for continued and periodic aging conditions

ri [8] prikazani su na slici 3. U slučaju kontinuiranog zagrijavanja, može se vidjeti brzo propadanje u prvih 40 godina; granična vrijednost od 50 % postiže se u 30-im godinama. Za slučaj izmjena u zagrijavanju, krivulja je nešto blaža i granična vrijednost dostignuta je u 60-oj godini. Zaključak je da, isto kao i za metodu mjerenja dubine utiska, životni vijek nuklearne elektrane se može produžiti na 60 godina uzimajući u obzir realne uvjete starenja (remont).

6.3 OIT/OITP metoda

Termička analiza mikro uzoraka mjerenjem vremena ili temperature potrebnih za induciranje oksidacije mjeri razinu anti-oksidansa u materijalu koji su dobri indikatori starenja materijala. Za uspoređivanje rezultata OIT metode, potrebno je definirati formu i veličinu uzorka, količinu kisika kojem je uzorak izložen, vrijeme stabilizacije dušika prije prihvaćanja kisika, tip i kalibraciju ispitne opreme, temperaturnu krivulju do postizanja temperature oksidacije, metodu određivanja početne vrijednosti oksidacije. Za OITP metodu potrebno je sve navedeno uz malu izmjenu; umjesto informacije o temperaturnoj krivulji do postizanja temperature oksidacije potrebno je definirati početnu temperaturu i nagib krivulje po kojoj temperatura raste.

7 UPRAVLJANJE ŽIVOTNIM VIJEKOM KABELA

Kabeli su izvor potencijalnih rizika za siguran rad NE. Proaktivnim upravljanjem starenja kabela osigurava se praćenje i kontrola funkcioniranja kabela kroz životni vijek elektrane. S obzirom da održavanje kabela nije planirano, sustavni pristup upravljanja životnim vijekom kabela postaje vrlo važno i donosi nekoliko dobrobiti: potvrđuje funkcionalnost opreme u svim pogonskim uvjetima (uključujuću i akcidentne događaje), osigurava projektiran životni vijek postrojenja i dostavlja podatke potrebne za odluku o produženju životnog vijeka, odnosno za obnavljanje licence za rad. Na slici 4 shematski je prikazan proces upravljanja životnim vijekom kabela, ali isti pristup primjenjuje se i za ostalu opremu važnu za sigurni rad nuklearne elektrane.

Proces upravljanja životnim vijekom kabela sastoji se od pet faza:

1. razumijevanje mehanizama starenja kabela,
2. koordinacija aktivnostima u procesu upravljanja,
3. aktivnosti upravljanja procesom starenja instaliranog kabela,

tinuous warming, quick deterioration is visible in the first 40 years; cut-off value of 50 % is achieved in the 30ies. In case of intermittent warming, the curve is somewhat milder and the cut-off value is achieved in the 60th year. The conclusion is that, just as with the method of indenter measurement, the nuclear power plant's lifespan can be extended to 60 years taking into consideration realistic aging conditions (repair).

6.3 OIT/OITP method

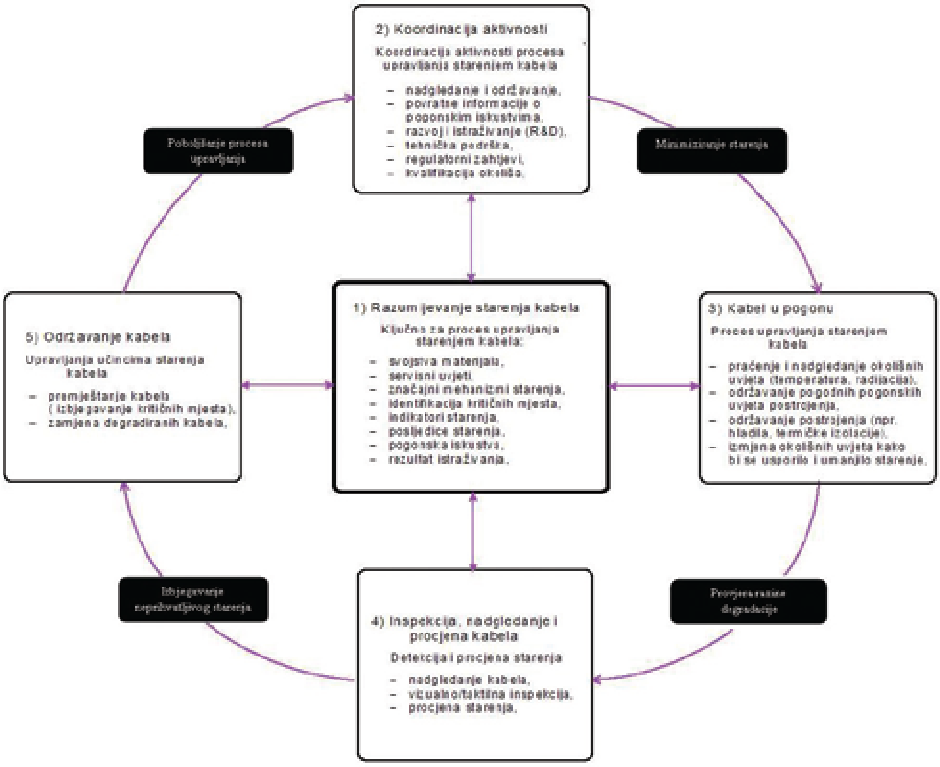
Thermal analysis of micro samples by measuring time or temperature necessary for oxidation induction measures the level of anti-oxidants in the material which are good indicators of material aging. For the purpose of comparison of the OIT method results, it is necessary to define the form and size of the sample, the volume of oxygen to which the sample is exposed, nitrogen stabilizing time before oxygen acceptance, type and calibration of the test equipment temperature curve up to the achievement of the oxidation temperature and the method of determination of the oxidation initial value. The OITP method requires all of the above with a small modification; in place of the information on the temperature curve up to the achievement of the oxidation temperature, it is necessary to define the initial temperature and curve pitch along which the temperature rises.

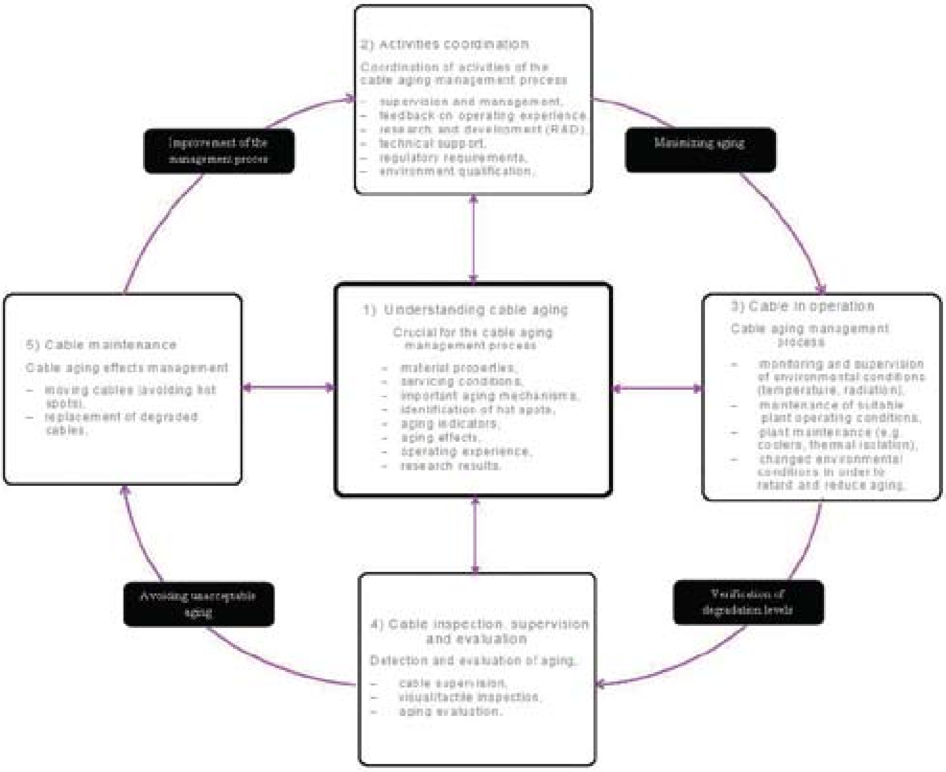
7 CABLE LIFESPAN MANAGEMENT

Cables are a source of potential risks for the safe operation of a nuclear power plant. Proactive management of cable aging provides for monitoring and controlling the functioning of cables throughout the power plant's lifespan. Considering the fact that cable maintenance was not planned, systematic approach to cable's lifespan management becomes very important and yields several advantages: confirmation of the functionality of the equipment in all operating conditions (including accidental events), ensuring the plant's engineered lifespan and provision of data necessary for the decision on extended lifespan, that is, for the renewal of the operating permit. Figure 4 schematically depicts the process of the cable's lifespan management, but the same approach is also applied to other safety-related equipment at the nuclear power plant.

Cable lifespan management process consists of five phases:

1. understanding cable aging mechanisms,
2. coordination of activities in the management process,
3. activities of installed cable aging management process,





Slika 4 — Shematski prikaz procesa upravljanja životnim vijekom kabela
Figure 4 — Schematic overview of the cable's lifespan management process

4. inspekcija, nadgledanje i procjena kabela,
5. održavanje.

Ključno za proces upravljanja je poznavanje mehanizama i razumijevanje procesa starenja. Nužno je poznavanje svojstava materijala, pogonskih uvjeta, postojanje kritičnih točaka, mehanizama starenja, prikladnih indikatora starenja i drugih podataka važnih za procjenu starenja. Podaci su većinom dobiveni iz projektne dokumentacije (na primjer, tehnička specifikacija kabela), rezultata nadzora, općeg pogonskog iskustva i rezultata istraživanja. Podaci bi se trebali povremeno osvježavati kako bi se omogućilo kontinuirano poboljšanje procesa upravljanja životnim vijekom kabela.

Programi upravljanja uključuju kvalifikaciju za uvjete okoliša, programe nadgledanja i održavanja pogona, povratne informacije o pogonskim iskustvima, istraživanje i razvoj te programe tehničke podrške. Iskustvo pokazuje da se učinkovitost procesa upravljanja povećava koordinacijom aktivnosti i sustavnim pristupom.
Koordinacija aktivnosti uključuje:

- dokumentaciju:
  - propisane regulativne zahtjeve i kriterije sigurnosti,
  - odgovarajuće programe i aktivnosti,
- opis mehanizama korištenih za koordinaciju i poboljšanje procesa upravljanja,
- koordinaciju prikladnih programa i aktivnosti,
- kontinuiran rad na poboljšanju.

Pogonski uvjeti značajno utječu na brzinu propadanja komponenti instaliranih u NE. Izlaganje kabela određenim uvjetima okoliša (temperatura, radijacija) može uzrokovati ubrzano starenje. Dakle, nadgledanjem i upravljanjem karakteristikama okoliša tijekom normalnog pogona značajno se može pridonijeti čuvanju opreme od ubrzanog starenja. To se postiže održavanjem određenih vrijednosti unutar pogonskih ograničenja.

Inspekcija, nadgledanje i procjena daju informaciju o postojanju i razini degradacije kabela prije kraja životnog vijeka na temelju kojih se, uz informacije iz prethodnih faza, donosi odluka o potencijalnoj zamjeni kabela.

8 ZAKLJUČAK

Produljenje životnog vijeka nuklearnih elektrana aktualna je tema nuklearne energetike pa su u okviru toga procjene starenja i upravljanje životnim vijekom komponenata važnih za sigurnost osobito značajne.

4. cable inspection, supervision and evaluation,
5. maintenance.

What is crucial for the management process is being acquainted with the mechanisms and understanding the aging process. It is necessary to be aware of material properties, operating conditions, of the existence of hot spots, aging mechanisms, suitable aging indicators and other data necessary for the evaluation of aging. Data have mostly been obtained from project documentation (for example, the cables' technical specifications), supervision results, general operating experience and research results. Data should be refreshed periodically in order to enable continued improvement of the cable lifespan management.

Management programmes include environmental qualification, plant supervision and maintenance programmes, feedback on operating experience, research and development and technical supervision programmes. Experience shows that the efficiency of the management process increases with the coordination of activities and systematic approach.
The coordination of activities includes:

- documentation:
  - prescribed regulatory requirements and safety criteria,
  - adequate programmes and activities,
- description of mechanisms used for coordination and improvement of the management process,
- coordination of adequate programmes and activities,
- continuous effort to improve.

Operating conditions significantly impact the speed of degradation of the components installed in the nuclear power plant. Exposing cables to certain environmental conditions (temperature, radiation) can cause accelerated aging. Therefore, the supervision and management of environmental conditions during normal operation can contribute significantly to the preservation of the equipment from accelerated aging. That is achieved by maintaining certain values within operating limits.

Inspection, supervision and evaluation provide information on the existence and level of degradation of the cable before the end of the lifespan based on which, with the information from the previous phases, decision is adopted on potential cable replacement.

8 CONCLUSION

Extension of nuclear power plant's lifespan is a current issue of the nuclear energy industry and for this reason evaluation of aging and the management of safety-related components' lifespan are extremely significant.

Iz perspektive sigurnosti, degradacija sustava, struktura i komponenti mora biti ispod kritičnih vrijednosti, u normalnim i abnormalnim pogonskim uvjetima. S obzirom da kabeli imaju dug životni vijek (40 godina), starenje kabela se nije razmatralo u kontekstu održavanja nuklearne elektrane. Međutim, radi produljenja životnog vijeka nuklearne elektrane, potrebno je utvrditi je li životni vijek kabela duži od projektom predviđenog.

Opisani su mehanizmi i učinci starenja kabela, prikazane su metode kojima se procjenjuje stupanj degradacije. Uočena je vrijednost procesa upravljanja starenjem kabela. Također, naglašena je važnost praćenja uvjeta okoliša za preciznu procjenu životnog vijeka kabela.

From the perspective of safety, degradation of systems, structure and components must be under critical values, in normal and abnormal operating conditions. Since the lifespan of cables is long (40 years), cable aging was not observed in the context of nuclear power plant management. However, for the purpose of extension of the nuclear power plant's lifespan, it is necessary to determine whether the cable's lifespan is longer than the engineered.

Mechanisms and cable aging effects were described, methods by which the degradation level are evaluated were shown. Importance of the cable aging management process has been noted. Moreover, the importance of supervision of the environmental conditions for the evaluation of the cable lifespan is stressed.

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PRIORITIZACIJA PROJEKATA REGIONALNE PRIJENOSNE MREŽE U CILJU POTPORE PROIZVODNOJ DJELATNOSTI I RAZVOJU TRŽIŠTA U JUGOISTOČNOJ EUROPI

PRIORITIZATION OF REGIONAL TRANSMISSION NETWORK PROJECTS TO SUSTAIN GENERATION AND MARKET DEVELOPMENT IN SOUTH EAST EUROPE

Goran Majstrović – Nijaz Dizdarević – Davor Bajs, Zagreb, Hrvatska

Regija jugoistočne Europe (SEE) prolazi kroz kontinuirani proces promjena u djelatnostima proizvodnje, prijenosa i distribucije električne energije. Ove promjene se reflektiraju u svakoj državi najprije u vidu reorganizacije vertikalno integriranih elektroprivrednih kompanija, nakon čega slijedi funkcionalno razdvajanje prijenosa električne energije od proizvodnje i distribucije. Promjene u energetskom sektoru također imaju utjecaja na filozofiju planiranja proizvodne i prijenosne djelatnosti, posebno s obzirom na činjenicu da je većina zemalja jugoistočne Europe u tranziciji. U posljednjih nekoliko godina izrađene su brojne studije u cilju uspostave i harmonizacije zajedničkog regionalnog i šireg europskog tržišta električne energije. U ovom radu razmatra se interakcija između najvažnijih studija o proizvodnoj i prijenosnoj djelatnosti u regiji, a koje su predstavljene i o kojima se raspravljalo u nekoliko prilika na regionalnoj razini (Atenski forumi, konferencije, radionice, internetske stranice, itd). Glavni cilj tih studija bio je asistirati Europskoj Komisiji (EC), Svjetskoj banci (WB) i donorima pri utvrđivanju indikativne ljestvice prioriteta ulaganja u proizvodnju električne energije i financiranja odgovarajuće električne infrastrukture iz regionalne perspektive i u skladu s ciljevima tržišta električne energije u jugoistočnoj Europi. Uži cilj ovog rada je analiza regionalne prijenosne mreže za ispitane scenarije razvoja, a u skladu s informacijama i zaključcima iz ažurirane studije proizvodne djelatnosti (tzv. GIS studija [1] i [4]). Krajnji rezultat bi trebao biti ljestvica prioriteta novih interkonektivnih vodova u regiji nužnih za plasman proizvodnje električne energije iz novih objekata i održivost tržišta električne energije.

The region of South East Europe (SEE) has been experiencing an ongoing process of changes in the energy sector in the areas of power generation, power transmission and power distribution. These changes are reflected in each country through reorganization of vertically integrated electric power utilities, followed by functional separation of transmission from generation and distribution. Changes in the energy sector have also affected the philosophy of generation and transmission planning since most of the SEE countries are transition countries. In order to establish and harmonize the common regional and the wider European electricity market, many study activities have been undertaken in the last few years. This paper deals with the interaction between the most important regional generation and transmission studies that were presented and discussed at different occasions at the regional level (Athens Fora, conferences, workshops, web sites etc.). The main aim of the studies was to assist the European Commission (EC), the World Bank (WB) and the donors in identifying the indicative priority list of investments in power generation and related electricity infrastructure from the regional perspective and in line with the objectives of SEE regional electricity market. The scope of work within this study was to analyze the transmission network for investigated scenarios and in accordance with the findings and conclusions from the updated GIS. The final result is supposed to be a list of new interconnection line priorities in the region necessary for new generation and future market sustainability.

Ključni pojmovi: interkonekcije; prioritizacija; regija jugoistočne Europe
Key words: interconnections; prioritization; SEE region

1. UVOD

Regija jugoistočne Europe (SEE) prolazi kroz kontinuirani proces promjena u djelatnostima proizvodnje, prijenosa i distribucije električne energije. Ove promjene se reflektiraju u svakoj državi najprije u vidu reorganizacije vertikalno integriranih elektroprivrednih kompanija, nakon čega slijedi funkcionalno razdvajanje prijenosa električne energije od proizvodnje i distribucije. Promjene u energetskom sektoru također imaju utjecaja na filozofiju planiranja proizvodnje i prijenosa, s obzirom na činjenicu da je većina zemalja jugoistočne Europe u tranziciji. U posljednjih nekoliko godina izrađene su brojne studije u cilju uspostave i harmonizacije regionalnog i šireg europskog tržišta električne energije. U ovom radu razmatra se interakcija između najvažnijih studija o proizvodnji i prijenosu električne energije u regiji [1], [2] i [3], a koje su predstavljene i o kojima se raspravljalo u nekoliko prigoda na regionalnoj razini (Atenski forumi, konferencije, radionice, internetske stranice, itd). Glavni cilj navedenih studija bio je pomoći Europskoj Komisiji (EC), Svjetskoj banci (WB) i donorima pri utvrđivanju indikativne ljestvice prioriteta ulaganja u proizvodnju električne energije, kao i u odgovarajuću regionalnu prijenosnu infrastrukturu u skladu s ciljevima tržišta električne energije u jugoistočnoj Europi.

Kronološki gledano, najvažnija studija o proizvodnoj djelatnosti u regiji dovršena je i objavljena 2004. godine [1] pod nazivom REBIS (eng. *Regional Balkans Infrastructure Study*) - GIS (eng. *Electricity and Generation Investment Study*). Cilj ove studije bio je utvrditi optimalnu veličinu, položaj i vrijeme za izgradnju novih proizvodnih objekata, kao i jačanje interkonektivnih prijenosnih moći u jugoistočnoj Europi tijekom idućih 15 godina (od 2005. do 2020. godine).

Godine 2007. u okviru radne grupe za planiranje prijenosne mreže u okviru SECI-ja (eng. South East Cooperation Initiative) EIHP iz Hrvatske i EKC iz Srbije zajedno su izradili studiju pod nazivom *Transmission Network Investment Criteria*. Cilj studije bio je uspostaviti kriterije i metodologiju planiranja regionalne prijenosne mreže u cilju prioritizacije projekata prijenosne djelatnosti u regiji u tržišnim uvjetima.

Zbog nekoliko značajnih promjena koje su se pojavile nakon 2004. godine, a koje se prije svega odnose na rast cijena plina i smanjenje cijene uvoznog ugljena, bilo je potrebno provesti ažuriranje originalne studije GIS-a, što je i provedeno 2007. godine. Cilj novog projekta bio je ažuriranje podataka i rezultata GIS studije iz 2004. godine (ažurirani GIS), sukladno tržišnim kretanjima, kao i s određenim revidiranim ograničenjima u razvoju elektroenergetskog sustava.

1 INTRODUCTION

The region of South East Europe (SEE) has been experiencing an ongoing process of changes in the energy sector in the areas of power generation, power transmission and power distribution. These changes are reflected in each country through reorganization of vertically integrated electric power utilities, followed by functional separation of transmission from generation and distribution. Changes in the energy sector have also affected the planning philosophy of generation and transmission since most of SEE countries are transition countries. In order to establish and harmonize the common regional and the wider European electricity market many study activities have been taken in last few years. This paper deals with the interaction between the most important regional generation and transmission studies [1], [2] and [3] that were presented and discussed on different occasions at the regional level (Athens Fora, conferences, workshops, web sites etc.). The main aim of the studies was to assist the European Commission (EC), the World Bank (WB) and the donors in identifying the indicative priority list of investments in power generation and the related electricity infrastructure from the regional perspective and in line with the objectives of the SEE regional electricity market.

Chronologically, the most important regional generation study was finished and issued in 2004 [1]. It was entitled the Regional Balkans Infrastructure Study (REBIS) – Electricity and Generation Investment Study (GIS). The aim of the study was to determine the optimal size, location and timing for the construction of new production capacities as well as the reinforcement of the main interconnection transmission capacity in the SEE region over the next 15 years (2005 to 2020).

In 2007, the study entitled the Transmission Network Investment Criteria was issued by the EIHP from Croatia and EKC from Serbia under the umbrella of the SECI Transmission System Planning Group. Its aim was to establish transmission system planning criteria and methodology for regional transmission project prioritization.

Due to a number of significant changes that have emerged since 2004, concerning primarily the growth of gas price and the decrease of imported coal price, the updating of the original GIS was required and accomplished in 2007, as well. The aim of the new project was to update the Generation Investment Study from 2004 (updated GIS) with some altered fuel prices, according to market development, as well as with some revised constraints to the power system development.

Posljedično, EIHP i EKC pokrenuli su i objavili 2007. godine studiju pod naslovom *Evaluation of Investments in Transmission Network to Sustain Generation and Market Development in SEE*. Glavni cilj ove studije bio je ažuriranje originalnih podataka i rezultata iz GIS-a u dijelu prijenosne mreže i pomoć Europskoj Komisiji (EC), Svjetskoj banci (WB) i donorima pri utvrđivanju indikativne ljestvice prioriteta ulaganja u interkonektivne vodove, kao i interne, unutardržavne vodove, a radi potpore ulaganjima u proizvodnju električne energije i tržišne razmjene. Svi nalazi, prijedlozi i zaključci iz prethodne studije (originalni GIS) provjereni su u novoj studiji, u skladu s navedenim promjenama i poštujući nove ljestvice prioriteta za izgradnju proizvodnih jedinica u jugoistočnoj Europi. U svim prethodno navedenim projektima analizirani su elektroenergetski sustavi: Albanije, Bosne i Hercegovine, Bugarske, Hrvatske, Makedonije, Crne Gore, Rumunjske, Srbije i Kosova. U ovom radu detaljno se razmatraju najznačajniji rezultati iz studije ažuriranog GIS-a.

2. CILJEVI STUDIJSKOG RADA

Osnovni cilj studije je scenarijska analiza prijenosne mreže, a u skladu s informacijama i zaključcima iz studije ažuriranog GIS-a. Krajnji rezultat trebala je biti ljestvica prioriteta novih interkonektivnih vodova u regiji koji su nužni za plasman nove proizvodnje i održivost regionalnog tržišta električne energije. Tokovi snaga i analiza sigurnosti ($n-1$) provedeni su za tri osnovna scenarija preuzeta iz ažuriranog GIS-a, uz četiri podscenarija za svaki od osnovnih scenarija. Ukupno je analizirano 12 scenarija. Kriterij sigurnosti temeljen na preopterećenju vodiča i naponskim profilima primijenjen je na svaki analizirani scenarij. Posebna pozornost posvećena je postojećim i planiranim interkonektivnim vodovima između elektroenergetskih sustava (država) jugoistočne Europe, kao i internim vodovima sa značajnim utjecajem na tokove snaga u regiji.

Utvrđena su područja očekivanih zagušenja unutar prijenosne mreže te su opisana određena rješenja za smanjenje uočenih preopterećenja. Korištenjem unaprijed utvrđenih kriterija investiranja u razvoj regionalne prijenosne mreže vrednovan je utjecaj pojedinih novih kandidata za izgradnju - interkonektivnih i internih vodova te je prema opisanoj metodologiji utvrđena njihova tehnička prioritetnost. Zbog nedostatka odgovarajućeg modela i ulaznih podataka ovaj rad nije obuhvatio daljnju ekonomsku analizu i prioritizaciju na temelju ekonomskih kriterija.

Consequently, in 2007 the study entitled the Evaluation of Investments in Transmission Network to Sustain Generation and Market Development in SEE was launched and issued by EIHP and EKC. The main objective of this study was to update the original GIS findings and to assist the EC, WB and the donors to identify the indicative priority list of investments in the main transmission interconnections and internal lines between the countries and sub-regions to sustain investments in power generation and support market exchanges over the study horizon. All findings, proposals and conclusions from the previous study (original GIS) were checked against the new changes, respecting the new priority list for generation units in the SEE region in accordance with the findings and conclusions from the updated GIS. In all the above mentioned projects the following parties were investigated: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Macedonia, Montenegro, Romania, Serbia and Kosovo. This paper deals with the main results of the last above mentioned study.

2 SCOPE OF WORK

The scope of work within this study was to analyze the transmission network for investigated scenarios and in accordance with the findings and conclusions from the updated GIS. The final result is supposed to be a list of new interconnection line priorities in the region necessary for new generation and future market sustainability. For three scenarios from the updated GIS, and four sub-scenarios for each GIS scenario, steady-state load flows were calculated and contingency ($n-1$) analyses were performed. The security criterion was based on lines overloading and voltage profile, and checked for each analyzed scenario. Special attention was focused on the existing and planned interconnectors between different SEE power systems (countries), as well as on internal lines with strong influence on regional flows. Total number of analyzed scenarios is set at 12.

Special attention was given to the analysis of overloading and voltage profile in the region. Possible network bottlenecks were identified and some solutions for the transmission system relief were described. The significance of new interconnection and internal lines candidates were evaluated. Candidate transmission projects were evaluated using predefined regional transmission investment criteria and technically prioritized according to the previously described prioritization methodology. Economic criteria evaluation and prioritization are not envisaged to be analyzed here due to the lack of appropriate model and input data at this moment.

Analizirani su sljedeći aspekti:

- proračun tokova snaga:
  utvrđivanje nisko, srednje i visoko opterećenih elemenata prijenosne mreže (niski do 20 %, srednji 20 % do 60 % i visoki iznad 60 % termičke granice opterećenja),
- analiza sigurnosti $(n-1)$:
  Adekvatnost sustava provjerena je korištenjem kriterija sigurnosti $(n-1)$. Popis elemenata pri analizi sigurnosti uključuje:

  - sve interkonektivne vodove;
  - sve 400 kV i 220 kV vodove, osim vodova koji zbog ispada uzrokuju otočni rad (u slučaju paralelnih i dvosistemskih vodova, razmatran je ispad jednog voda);
  - svi 400/200 kV transformatori (u slučaju paralelnih transformatora razmatran je zastoj jednog transformatora).
- naponski profil, za naponske razine veće i jednake 220 kV:
  Ograničenja napona utvrđena su u odnosu na pogonske i planerske standarde koji se koriste u ovoj regiji, i to u slučajevima pune raspoloživosti i raspoloživosti $(n-1)$ elementa mreže. Iako su u interventnim slučajevima za neke naponske razine dopuštena veća odstupanja napona, ista ovdje nisu uzeti u obzir.

3. ULAZNI PODACI STUDIJE

3.1. Proizvodnja električne energije

U ažuriranom GIS-u razvoj proizvodne djelatnosti optimiziran je za razdoblje od 15 godina (od 2005. do 2020. godine), i to za sljedeća tri scenarija:

- izolirani pogon pojedinog elektroenergetskog sustava,
- zajednički regionalni pogon elektroenergetskih sustava, i
- pogon u tržišnim uvjetima.

U sklopu tih analiza izvršena je revizija osnovnog scenarija GIS-a, s najvjerojatnijim cijenama nafte i prirodnog plina. To je bio scenarij prema kojem se za sve stare termoelektrane predviđa postupak revitalizacije u skladu s planovima nadležnih elektroprivrednih kompanija. Raspored realizacije planiranih projekata i ostale informacije ostale su zbog dosljednosti iste kao i u originalnoj studiji, iako su određene manje promjene već nastupile u realizaciji projekata, troškovima, dizajnu, itd. Nadalje, analizirani su i slučajevi koji se odnose na različite visine naknada za emisiju CO_2. Ažuriranje GIS-a u dijelu prijenosne djelatnosti provedeno je prema sljedećim scenarijima razvoja proizvodne djelatnosti unutar elektroenergetskog sustava:

The following issues were analyzed:

- load flow calculations:
  To identify low, medium and high loaded elements in the transmission network, (low to 20 %, medium 20 % to 60 % and highly loaded over 60 % of current limit),
- security $(n-1)$ analysis:
  The system adequacy is checked for operating conditions using the $(n-1)$ contingency criterion. The list of contingencies includes:

  - all interconnection lines,
  - all 400 kV and 220 kVlines, except the lines which outages cause island operation (in case of parallel lines and double circuit lines, outage of one line-circuit is considered),
  - all transformers 400/200 kV (in case of parallel transformers, outage of one transformer is considered),
- voltage profile, for all the voltage levels of 220 kV and above:
  Voltage limits are given according to the operational and planning standards used in the monitored region, and they will be used for full topology and $(n-1)$ analyses. Although in emergency conditions, for some voltage levels, wider voltage limits are allowed, these are not taken into consideration.

3 STUDY INPUT DATA

3.1 Regional generation sample

In the updated GIS, the expansions of the generation system were optimized over the 15 years horizon (2005 to 2020) for the following three scenarios:

- isolated operation of each power system,
- regional operation of power systems, and
- market conditions.

Within those analyses, a revision of the GIS baseline scenario was performed, with the most probable prices assumed for oil and natural gas. This was the scenario in which all of the old thermal power plant units are scheduled to go through the rehabilitation process according to the plans given by the utilities. The implementation schedules of the planned projects and all other information were kept the same, for consistency purposes, even though some changes have actually occurred in the actual project schedules, costs, design etc. Cases concerning different CO_2 taxes were analyzed as well. The update of the GIS has been performed with the following generation scenarios of the power system development:

- osnovni scenarij sa službenim programom revitalizacije (GIS sc1),
- osnovni scenarij s ekonomski opravdanim programom revitalizacije (GIS sc2),
- scenarij s visokim cijenama goriva (GIS sc3),
- scenarij s niskim cijenama goriva (GIS sc4),
- scenarij 20 EUR/t CO_2 (GIS sc5),
- scenarij 30 EUR/t CO_2 (GIS sc6),
- scenarij s visokim uvozom (GIS sc7),
- scenarij izgradnje hidroelektrana u varijanti visokih cijena goriva (GIS sc8),
- scenarij izgradnje hidroelektrana u varijanti 20 EUR/t CO_2 (GIS sc9), i
- scenarij izgradnje hidroelektrana u varijanti 30 EUR/t CO_2 (GIS sc10).

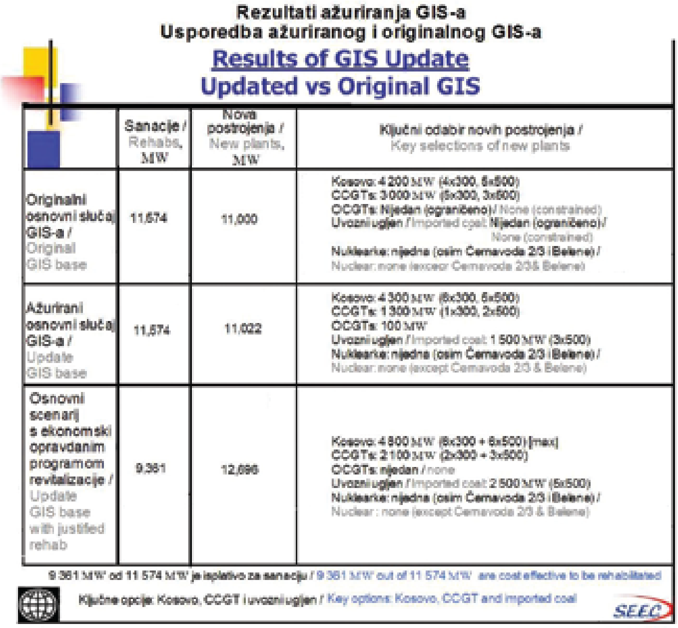
Ažurirana studija GIS rezultirala je značajnim razlikama u odnosu na originalnu studiju (slika 1). Naime, između osnovnih slučajeva sa službenim programom revitalizacije i onih s ekonomski opravdanim programom revitalizacije postoje razlike koje se odnose na sljedeće:

- manja snaga novim KTE (1 300 MW u GIS sc1 i 2 100 MW u GIS sc2 u odnosu na 3 000 MW u originalnom GIS-u), i
- povećana uporaba uvoznog ugljena (1 500 MW u GIS sc1 i 2 500 MW u GIS sc2 u odnosu na 0 MW u originalnom GIS-u).

- base case with the official rehabilitation program (GIS sc1),
- base case with the justified rehabilitation program (GIS sc2),
- high fuel price scenario (GIS sc3),
- low fuel price scenario (GIS sc4),
- 20 EUR/t CO_2 scenario (GIS sc5),
- 30 EUR/t CO_2 scenario (GIS sc6),
- high electricity import scenario (GIS sc7),
- hydro power plants and high fuel price scenario (GIS sc8),
- hydro power plants with 20 EUR/t CO_2 scenario (GIS sc9), and
- hydro power plants with 30 EUR/t CO_2 scenario (GIS sc10).

The updated GIS study resulted in significant differences in comparison with the original study (Figure 1). i.e. in the basic cases with the official rehabilitation program and the justified rehabilitation program, there are differences concerning the following:

- smaller amount of new CCGT (1 300 MW in GIS sc 1 and 2 100 MW in GIS sc2 in comparison with 3 000 MW in original GIS), and
- increased usage of imported coal (1 500 MW in GIS sc1 and 2 500 MW in GIS sc2 in comparison with 0 MW in the original GIS).



Rezultati ažuriranja GIS-a
Usporedba ažuriranog i originalnog GIS-a
Results of GIS Update
Updated vs Original GIS

	Sanacije / Rehabs, MW	Nova postrojenja / New plants, MW	Ključni odabir novih postrojenja / Key selections of new plants
Originalni osnovni slučaj GIS-a / Original GIS base	11,574	11,000	Kosovo: 4 200 MW (4x300, 6x500) CCGTs: 3000 MW (5x300, 3x500) OCGTs: Nijedan (ograničeno)/ None (constrained) Uvozni ugljen / Imported coal: Nijedan (ograničeno)/ None (constrained) Nuklearke: njedna (osim Černavoda 2/3 i Belene) / Nuclear: none (excecr Cernavoda 2/3& Belene)
Ažurirani osnovni slučaj GIS-a / Update GIS base	11,574	11,022	Kosovo: 4 300 MW (6x300, 5x500) CCGTs: 1 300 MW (1x300, 2x500) OCGTs: 100 MW Uvozni ugljen / Imported coal: 1 500 MW (3x500) Nuklearke: njedna (osim Černavoda 2/3 i Belene) / Nuclear: none (except Cernavoda 2/3 & Belene)
Osnovni scenarij s ekonomski opravdanim programom revitalizacije / Update GIS base with justified rehab	9,361	12,096	Kosovo: 4 800 MW (6x300 + 6x500) [max] CCGTs: 2 100 MW (2x300 + 3x500) OCGTs: njedan / none Uvozni ugljen / Imported coal: 2 500 MW (5x500) Nuklearke: njedna (osim Černavoda 2/3 i Belene) / Nuclear : none (except Cernavoda 2/3 & Belene)

9 361 MW od 11 574 MW je isplativo za sanaciju / 9 361 MW out of 11 574 MW are cost effective to be rehabilitated

Ključne opcije: Kosovo, CCGT i uvozni ugljen / Key options: Kosovo, CCGT and imported coal

Slika 1 — Najznačajniji rezultati iz ažuriranog GIS-a [4]
Figure 1 — The main results of updated GIS [4]

Prilikom modeliranja angažmana generatora poštivala se uobičajena i očekivana elektroenergetska bilanca sustava u regiji. Angažman generatora

Modeling of generators engagement respected regional power balance. Generators engagement in each GIS country were determined by the analiziran u studiji za svaku državu GIS-a određivali su predstavnici odgovarajućeg operatora prijenosnog sustava, a njihove odluke temeljile su se na postojećoj praksi raspodjele i graničnim troškovima, kao i na temelju tržišnog angažmana iz originalnog GIS-a. Opskrba država električnom energijom (koje nisu razmatrane u GIS-u, ali su uključene u model prijenosnog sustava) također su modelirane prema UCTE System Adequacy Forecast [5].

Međutim, pojavili su se problemi pri analizi prijenosne mreže. Naime, ažurirani GIS pruža informacije o tipovima i veličinama novih elektrana za različite scenarije planiranja, ali bez informacija o njihovoj lokaciji i angažmanu, za razliku od originalnog GIS-a iz 2004. godine. Razlog je u tome što se pri izradi ažuriranog GIS-a koristio samo WASP model, dok je pri izradi originalne GIS studije korišten i GTmax model. Takvi rezultati su iznimno nepraktični za planiranje prijenosnog sustava zbog toga što sadrže mnogo nesigurnosti koje se odnose na različite moguće lokacije velikih elektrana i njihov nepoznat angažman. Naime, razvoj prijenosnog sustava usko je vezan uz lokaciju novih elektrana i njihov angažman (ponudu), tako da je bilo potrebno definirati odgovarajuće scenarije planiranja prijenosnog sustava.

Zbog nepoznate lokacije nekoliko tisuća MWs u nekoliko scenarija iz ažuriranog GIS-a, adekvatnost prijenosnog sustava analizirana je samo za tri scenarija, za koje je bilo moguće odrediti lokacije novih elektrana:

- osnovni scenarij sa službenim programom revitalizacije (GIS sc1),
- osnovni scenarij s ekonomksi opravdanim programom revitalizacije (GIS sc2), i
- scenarij izgradnje hidroelektrana u varijanti visokih cijena goriva (GIS sc8).

Pri tom su u obzir uzeti svi preduvjeti i pretpostavke iz ažuriranog GIS-a za ova tri scenarija, a koji se odnose na broj i angažman TE. Nove, planirane TE, plinske TE i KTE, također su uzete u obzir i analizirane za razdoblje do 2015. godine (tablica 1). Snaga proizvodnih jedinica prikazana je na pragu elektrane (nominalna snaga generatora umanjena za vlastitu potrošnju proizvodnog bloka). Vlastita potrošnja standardnih TE može varirati između 5 % do 10 %, dok u slučaju plinske TE ili KTE doseže do 5 % instaliranog kapaciteta. S obzirom na to da je vlastita potrošnja HE obično manja od 1 %, nominalna snaga svake HE predstavlja istodobno i snagu na pragu elektrane.

Unatoč tomu, s obzirom na to da su sve analize u ažuriranom GIS-u provedene korištenjem WASP softvera, izlazni rezultati za tri odabrana scenarija sadrže i neke generičke elektrane (na lignit, uvozni ugljen ili plin) s odgovarajućom proizvodnjom, ali bez određenja točne lokacije ili načina priključivanja na

representatives from TSOs, based on the existing dispatching practice and marginal costs, as well as on the basis of the original GIS market engagement. Electricity supply of the countries (that were not considered in the GIS but were included in the transmission system model) were also modeled according to the UCTE System Adequacy Forecast [5].

But, the problems occurred with the choice of transmission study scenarios. Namely, the updated GIS gives only types and sizes of new power plants for different planning scenarios, without their location and market engagement, unlike the original GIS from 2004. The reason for that is the use of the WASP model only, whereas the GTmax model was used in the previous stage as well. Such results are extremely inconvenient for transmission system planning because of many uncertainties related to different possible locations for large power plants and their unknown market engagement. Transmission system development largely depends on the new power plants' location and their engagement (market bids), so additional planning scenarios for transmission system have to be defined.

Due to unknown location of several thousands of MWs in a number of updated GIS scenarios, transmission system adequacy was analyzed for three scenarios only, assuming that it will be possible to determine locations of new power plants for these scenarios:

- base case with official rehabilitation program (GIS sc1),
- base case with justified rehabilitation program (GIS sc2), and
- hydro power plants and high fuel price scenario (GIS sc8).

All prerequisites and assumptions from the update of the GIS for these selected scenarios were taken into account regarding the number and engagement of TPPs. New planned TPPs, OCGTs and CCGTs are also taken into account and implemented in the period until 2015 (Table 1). All generation unit output values are given as grid output values (nominal power of generator reduced by generation block self consumption). Self consumption of standard TPPs may vary from 5 % to 10 %, while for OCGT or CCGT it goes up to 5 % of installed capacity depending on the processes covered by this supply. Since the self consumption of HPPs is usually less than 1 %, nominal power for each generator represents at the same time the grid output.

Nevertheless, since all the analyses in the update of GIS were performed with the WASP software, result outputs for three selected sceenergetski sustav. U tim slučajevima odabrana je zamjena elektrana s onima iz skupine elektrana sa sličnom ili istom instaliranom snagom koje nisu razmatrane u GIS-u, ali su navedene u regionalnom modelu prijenosne mreže (RTSM, eng. *Regional Transmission System Model* [7]) razvijanom u sklopu projekta SECI (tablica 2). Na taj način se održala dosljednost s prethodnim GIS studijama, a implementirani su ažurirani podaci iz modela SECI za 2015. godinu.

narios contain some generic power plants (lignite, imported coal or gas power plants) with respective generation, but without the exact location given, or the manner of connection to the power system. In such cases, power plant replacements were chosen from the group of power plants with similar or same installed power which are not considered in the GIS, but are present in the SECI Regional Transmission System Model (RTSM) (Table 2). In this way, consistency with the previous GIS studies is maintained and updates, given in the SECI model for 2015, were implemented.

Tablica 1 – Nove proizvodne jedinice planirane u ažuriranoj verziji GIS-a od 2005. do 2015. godine
Table 1 – New generation units planned in update of GIS from 2005 till 2015

	Službeni osnovni slučaj / Base case official		Opravdani osnovni slučaj / Base case justified		Visoka cijena griva i hidroelektrane / High gas price & hydro	
Područje / Area	Elektrana / Power plant	Instalirana snaga / Instaled power, MW	Elektrana / Power plant	Instalirana snaga / Instaled power, MW	Elektrana / Power plant	Instalirana snaga / Instaled power, MW
Albanija / Albania	TE / TPP Vlora (2010.)	132	TE / TPP Vlora (2010.)	132	TE / TPP Vlora (2010.)	132
Bugarska / Bulgaria	TE / TPP Maritsa Istok I	2x275	TE / TPP Maritsa Istok I	2x275	TE / TPP Maritsa Istok I	2x275
	NE / NPP Belene	1x930	NE / NPP Belene	1x930	NE / NPP Belene	1x930
Bosna i Hecegovina / Bosnia and Hercegovina					HE / HPP Buk Bijela	3x150
					HE / HPP Srbinje/Foča	3x18,5
					HE / HPP Glavatičevo	172
					HE / HPP Dabar	160
Hrvatska / Croatia						
Makedonija / Macedonia						
Crna Gora / Montenegro					HE / HPP Komarnica	168
					HE / HPP Zlatica	3x18,5
					HE / HPP Kostanica	552
					HE / HPP Andrijevo	200
Srbija (sa UNMIK-om) / Serbia (with UNMIK)	TE / TPP Kosovo C (UNMIK) 1-1	1x450	TE / TPP Kosovo C (UNMIK) 1-5	1x450		
	TE / TPP Kolubara B	2x320	TE / TPP Kolubara B	2x320	TE / TPP Kolubara B	2x320
	TE / TPP Kosovo B (UNMIK) 3-5	2x275	TE / TPP Kosovo B (UNMIK) 3-8	4x275		
					HE / HPP Zhur (UNMIK)	293
Rumunjska / Romania	PTE / GTPP Bucuresti sud 1	100	PTE / GTPP Bucuresti sud 1	100	PTE / GTPP Bucuresti sud 1	100
	PTE / GTPP Bucuresti sud 2	100	PTE / GTPP Bucuresti sud 2	100	PTE / GTPP Bucuresti sud 2	100
	PTE / GTPP Bucuresti west 1	100	PTE / GTPP Bucuresti west 1	100	PTE / GTPP Bucuresti west 1	100
	PTE / GTPP Bucuresti west 2	100	PTE / GTPP Bucuresti west 2	100	PTE / GTPP Bucuresti west 2	100
	NE / NPP Cerna Voa 2	664	NE / NPP Cerna Voa 2	664	NE / NPP Černa Voa 2	664
	NE / NPP Cerna Voa 3	664	NE / NPP Cerna Voa 3/ NPP Cerna Voa 3	664	NE / NPP Černa Voa 3	664
GIS ukupno / total	BCO nova generacija / new generation	5 255	BCJ nova generacija / new generation	5 530	HGPH nova generacija / new generation	6 086

Tablica 2 – Nepoznate generičke elektrane u GIS-u i kandidati za njihovu zamjenu
Table 2 – Unknown generic power plants in GIS and their replacement candidates

Scenario / Scenario	Nepoznata elektrana / Unknown power plant	Instalirana snaga, / Installed power, MW	Kandidat za zamjenu / Replacement candidate
Službeni osnovni slučaj / Base case offcial	Kombi / Combined cycle	288	CCGT Skopje (MK)
	Kombi / Combined cycle	480	CCGT Sisak + CCGT Osijek (HR)
Ukupna proizvodnja s nepoznatom lokacijom / Total generation with unknown location		768	
Opravdani osnovni slučaj / Base case justified	Kombi / Combined cycle	288	CCGT Skopje (MK)
	Kombi / Combined cycle	480	CCGT Sisak + CCGT Osijek (HR)
	Kombi / Combined cycle	480	CCGT Novi Sad (RS)
	Uvozni ugljen / Imported coal	470	TE Plomin G3 (HR) / TPP Plomin G3 (HR)
Ukupna proizvodnja s nepoznatom lokacijom / Total generation with unknown location		1 718	
Visoka cijena goriva i hidroelektrane / High gas price & hydro	Kombi / Combined cycle	288	CCGT Skopje (MK)
	Kombi / Combined cycle	480	CCGT Sisak + CCGT Osijek (HR)
	Podkritičan lignit / Lignite subcritical	275	TE / TPP Kosovo B G3 (RS/UNMIK)
	Podkritičan lignit / Lignite subcritical	275	TE / TPP Kosovo B G4 (RS/UNMIK)
	Podkritičan lignit / Lignite subcritical	275	TE / TPP Kosovo B G5 (RS/UNMIK)
	Podkritičan lignit / Lignite subcritical	450	TE / TPP Kosovo B G1 (RS/UNMIK)
	Superkritičan uvozni ugljen / Imported coal supercritical	470	TE / TPP Plomin G3 (HR)
	Superkritičan uvozni ugljen / Imported coal supercritical	470	TE / TPP Martisa Istok III G5 (BG)
	Superkritičan uvozni ugljen / Imported coal supercritical	470	TE / TPP Martisa Istok III G6 (BG)
Ukupna proizvodnja s nepoznatom lokacijom / Total generation with unknown location		3 453	

Osim novih konvencionalnih elektrana na fosilna goriva u ažuriranom GIS-u uzet je u obzir jedan novi 1 000 MW nuklearni reaktor u NE Belene (Bugarska) i dva nova 700 MW reaktora u NE Černa Voda (Rumunjska). Osim toga, s obzirom na povišenu cijenu goriva, u scenariju visoke cijene plina i izgradnje hidroelektrana (sc8), očekuje se puno veća izgradnja hidroelektrana pa su sukladno tome i takvi objekti uključeni u modele.

Sve nove elektrane modelirane su sukladno podacima prikupljenim od nadležnih elektroprivrednih kompanija i operatora prijenosnog sustava. U slučajevima kada su načini priključka elektrane bili nepoznati, ta elektrana je priključena na najbližu transformatorsku stanicu s dostatnim kapacitetom prihvata (na primjer, HE Dabar i HE Glavatičevo).

U postupku određivanja lokacija za nove elektrane, također su se poštivali i dostupni planovi razvoja regionalne mreže plinovoda iz 2007. godine (slika 2).

Geografski položaji novih i doznačenih elektrana do 2015. godine prikazani su na slikama 3 do 5.

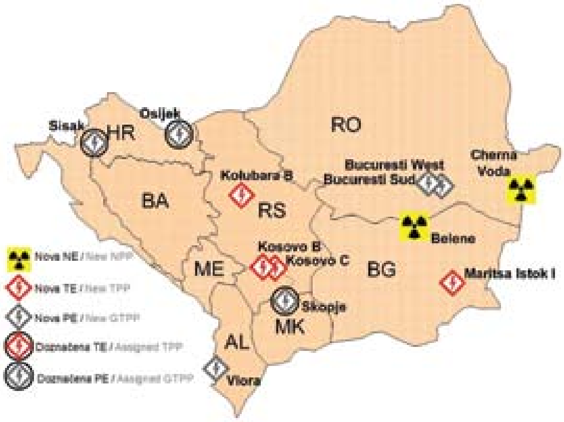
Besides new conventional fossil fuel fired power plants, one new 1 000 MW nuclear reactor in NPP Belene (Bulgaria) and two new 700 MW reactors in NPP Cherna Voda (Romania) were also taken into consideration according to update of GIS. Other than that, in the High Gas Price & Hydro Scenario, due to increased fuel price, much higher development of HPPs is expected and introduced in the models accordingly.

All new power plants are modeled in the power systems according to the information gathered from the corresponding electric power utilities and the TSOs. In some cases, when the means of connection of power plant were unknown, it was connected to the nearest substation with a capability to accept the additional power injection (i.e. HPP Dabar and HPP Glavaticevo).

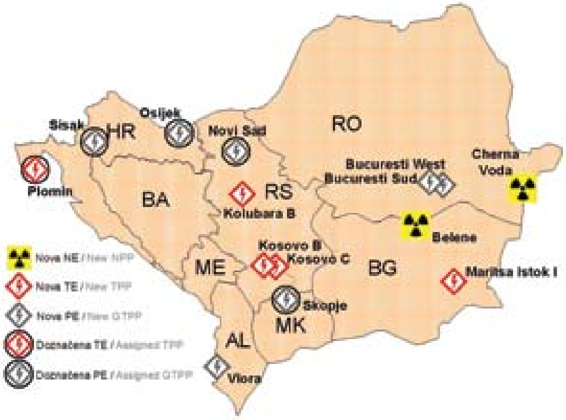
In the process of determination of locations for new power plants, the regional gas network development plans available in 2007 were also respected (Figure 2).

Geographical positions of new and assigned power plants until 2015 are shown in Figures 3 to 5.

Slika 2 — Planovi razvoja plinske mreže u regiji (uključujući naftovod PEOP) [6]
Figure 2 — Gas network development plans in the region (including PEOP oil pipeline) [6]



Slika 3 — Osnovni scenarij sa službenim planom revitalizacije – Položaj novih elektrana iz GIS-a i doznačene lokacije za elektrane s prethodno nepoznatom lokacijom
Figure 3 — Base Case Official – Location of new power plants in GIS and assigned locations for power plants with previously unknown location



Slika 4 — Osnovni scenarij s ekonomski opravdanim programom revitalizacije – Položaj novih energetskih postrojenja u GIS-u i doznačene lokacije za elektrane s prethodno nepoznatom lokacijom
Figure 4 — Base Case Justified – Location of new power plants in GIS and assigned locations for power plants with previously unknown location

Slika 5 — Scenarij visokih cijena goriva i izgradnje hidroelektrana – Položaj novih energetskih postrojenja u GIS-u i doznačene lokacije za elektrane s prethodno nepoznatom lokacijom

Figure 5 — High Gas Price & Hydro – Location of new power plants in GIS and assigned locations for power plants with previously unknown location

3.2. Potrošnja električne energije

Modeliranje opterećenja u ovoj studiji provedeno je na isti način kao i u originalnom GIS-u. Modelirana su tri nivoa opterećenja:

- zimsko vršno opterećenje,
- ljetno maksimalno opterećenje, i
- ljetno minimalno opterećenje.

Dakle, definirani su različiti modeli opterećenja koji predstavljaju raspon očekivane nesigurnosti. Opterećenja sustava koji nisu razmatrani u okviru GIS-a, ali su uključeni u model prijenosne mreže, modelirana su prema ranije navedenom dokumentu UCTE System Adequacy Forecast 2006 till 2015.

Predviđanje zimskog vršnog opterećenja 2015. godine preuzeto je iz originalnog GIS-a i ažuriranih podataka GIS-a. Ukupno vršno opterećenje 2015. za regiju GIS-a (Albanija, Bosna i Hercegovina, Bugarska, Hrvatska, Makedonija, Crna Gora, Rumunjska, Srbija i Kosovo) postavljeno je na 33 151 MW. Ovo opterećenje korišteno je za modeliranje osnovnog scenarija sa službenim programom revitalizacije, dok su za osnovni scenarij s ekonomski opravdanim programom revitalilzacije (33 188 MW) i scenarij visoke cijene plina i izgradnje hidroelektrana (33 193 MW) korištene nešto više razine opterećenja. Ovo povećanje opterećenja nastalo je uslijed odgovarajućeg dodatnog iznosa vlastite potrošnje novih proizvodnih jedinica (TE), koja su pribrojena polaznom iznosu opterećenja. Pojedinačna opterećenja sustava u regiji preuzeta su iz osnovnog scenarija originalnog GIS-a za 2015. godinu i uvedena u PSS/E model tokova snaga.

3.2 Regional demand sample

The modeling of the demand side applied in this study was the same as in the original GIS. Concerning the analyzed demand situations, three load levels were modeled:

- winter peak load,
- summer maximum load, and
- summer minimum load.

Initial models were used to create different models representing future uncertainties. Electricity demand of the countries that were not considered in the GIS,but were included in the transmission system model were modeled according to the UCTE System Adequacy Forecast 2006 till 2015.

The demand forecast for the 2015 winter regime is taken consequently from the original GIS and the update of the GIS, since this value was calculated and given as a reference for all calculations. Total peak demand for the GIS region (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Macedonia, Montenegro, Romania, Serbia and Kosovo) is set to 33 151 MW. This consumption was used in the modeling of the Base Case Official Scenario, while slightly increased values of demand were used for the Base Case Justified Scenario (33 188 MW) and High Gas Price & Hydro Scenario (33 193 MW). This increase of demand originates from the addition of self consumption for the new TPP generation units, which were added according to the update of the GIS. Particular demands of each power system in GIS region are taken from the original GIS base case for 2015 and introduced into PSS/E load flow models.

3.3. Regionalna bilanca i scenarij razmjena

Tablice razmjena između pojedinih zemalja regije usklađene su i odobrene od strane predstavnika nadležnih operatora prijenosnog sustava. Također su usklađene razmjene zemalja koje nisu razmatrane u GIS-u, ali su uključene u model prijenosnog sustava [8]. Razmatrane su tri razine regionalne bilance, ovisno o hidrološkim prilikama (suha i vlažna hidrologija):

- uravnotežena bilanca – vlažna hidrologija (proizvodnja u regiji GIS-a jednaka je opterećenju),
- vlažna hidrologija (izvoz iz regije GIS-a, posebno u UCTE ili Italiju), i
- suha hidrologija (uvoz u regiju GIS-a iz CENTREL-a i Ukrajine).

Režim uravnotežene bilance predstavlja obrazac proizvodnje u kojem je regija GIS-a samoodrživa, i to u smislu ravnoteže između proizvodnje električne energije i njene potrošnje. Proizvodnja TE preuzeta je iz originalnog i ažuriranog GIS-a, dok je proizvodnja HE proizašla iz usporedbe podataka iz originalnog GIS-a (scenarij prosječne hidrologije) i SECI RTSM-a za zimsko razdoblje. Naime, potrebno je istaknuti da je regionalni zimski model SECI-a za 2015. godinu temeljen na vlažnoj hidrologiji. S obzirom da je cilj bio dobiti smanjenu proizvodnju HE (uravnoteženu bilancu), u usporedbi angažmana HE u GIS i SECI modelu odabrana je niža od ove dvije vrijednosti. Na taj je način dobiven scenarij s prosječnom hidrologijom i programom razmjene pri uravnoteženoj bilanci.

Pri analizi je pretpostavljeno da hidrološke prilike jednako djeluju na angažman HE u cijeloj regiji GIS-a. U režimu suhe hidrologije regija GIS-a ima proizvodni deficit zbog znatno niže proizvodnje HE. Dok angažman TE u ovom režimu ostaje isti kao i u režimu uravnotežene bilance, angažman HE je potpuno preuzet iz scenarija suhe hidrologije iz originalnog GIS-a.

U režimu vlažne hidrologije regija GIS-a ostvaruje višak proizvodnje zbog znatno veće proizvodnje HE. Angažman TE u ovom režimu ostaje isti kao i kod režima uravnotežene bilance, ali je pretpostavljen viši angažman svih jedinica HE u usporedbi s originalnim GIS-om i SECI RTSM.

Dakle, kako je ranije rečeno, u studiji ažuriranog GIS-a korišteno je dvanaest scenarija za strukturu proizvodnje, njenu revitalizaciju i izgradnju, a koji se zasnivaju na najvjerojatnijem stanju s rezervama goriva, cijenama goriva, utjecajem na okoliš i praktičnom iskustvu. Svi ti scenariji su analizirani pomoću WASP softvera s istim

3.3 Regional power balance and exchange scenario

Exchange tables between the GIS countries were harmonized and approved by the representatives of each regional TSO. Power exchanges of the countries not considered in the GIS but included in the transmission system model were harmonized as well. Three levels of regional power balance were observed, depending on the hydrological conditions (dry and wet hydrology):

- zero balance - wet hydrology (generation in GIS region covers its own demand),
- wet hydrology (export from GIS region to UCTE or Italy particularly), and
- dry hydrology (import of GIS region from CENTREL and Ukraine).

The zero balance regime represents a generation pattern in which the GIS region is self-sustainable in terms of balance between power generation and consumption. Generation of TPPs is taken from the original GIS and the update of the GIS, while generation of HPPs is derived from the comparison of data from the original GIS (average hydrology scenario) and the SECI winter RTSM. It must be pointed out that the SECI RTSM for winter 2015 is a wet hydrology model. Since the aim was to get a reduced generation of HPPs (with high water inflows), the lower value of generation was taken for each generator in this comparison. This way, a more average hydrology scenario with zero balance exchange program was obtained.

Low water inflows (often marked as dry hydrology), which are considered to be the same for the entire GIS region, affect the engagement of HPPs. In this regime, the GIS region has a generation deficiency due to much lower generation of HPPs. While the engagement of TPPs in this regime remains the same as it is in the zero balance regime, the engagement of HPPs is completely taken from the original GIS dry hydrology scenario.

High water inflows (often marked as wet hydrology), which are also considered to be the same for entire GIS region, affect the engagement of HPPs in the opposite manner. In this regime, the GIS region has a generation surplus due to much higher generation of HPPs. The engagement of TPPs in this regime remains the same as it is in the zero balance regime, but the engagement of HPPs is taken to be at a higher value of generation for each unit compared with the original GIS and the SECI RTSM.

According to the update of the GIS, ten scenarios for generation structure, rehabilitation and expansion were given based upon most probable fuel reserves, fuel prices, ecological impacts and common practice. All of these scenarios were analyzed in the WASP software with the same consumption at the regional opterećenjem na regionalnoj razini (3 151 MW). Programi razmjene snaga u regiji GIS-a definiranih u modelu PSS/E sažeti su u tablici 3. Negativni znak ispred snage razmjene podrazumijeva uvoz.

level (3 151 MW, taken from the original GIS). Three scenarios were chosen for further analyses in the present study since they have the highest compatibility with the situation in the analyzed region:

— base case with the official rehabilitation program (Base Case Official Scenario),
— base case with the justified rehabilitation program (Base Case Justified Scenario), and
— hydro power plants and high fuel price (High Gas Price & Hydro Scenario).

Exchange programs of the GIS region which can be read from the previous PSS/E outputs are summoned in Table 3. The negative mark in front of the exchange power means that that area or the region is importing energy.

Tablica 3 – Programi razmjene u regiji GIS-a za svaki scenarij
Table 3 – Exchange programs of GIS region for each scenario

Scenarij / Scenario	Nulta ravnoteža / Zero balance, MW	Izvoz u UCTE (vlažna hidrologija) / Export to UCTE (wet hydrology), MW	(Izvoz u Italiju (vlažna hidrologija) / Export to Italy (wet hydrology), MW	Uvoz iz CENTREL i Ukrajine (suha hidrologija) / Import from CENTREL and Ukraine (dry hydrology), MW
Osnovni scenarij sa službenim programom revitalizacije / Base Case Official	0	1 850	1 850	–2 450
Osnovni scenarij s ekonomski opravdanim programom revitalizacije / Base Case Justified	0	2 170	2 170	–1 990
Scenarij visoke cijene goriva i izgradnje hidroelektrana / High Gas Price&Hydro	0	3 020	3 020	–2 100

4 NESIGURNOSTI PRI PLANIRANJU PRIJENOSNE MREŽE

Osim navedenih ulaznih podataka, pojavile su se i druge značajne nesigurnosti u procesu planiranja mreže zbog dereguliranog tržišnog okruženja. Najvažnije nesigurnosti za jugoistočnu Europu u pogledu razvoja prijenosnog sustava iznesene su u [3]. To su:

— veličine i lokacije novih elektrana,
— hidrološki uvjeti,
— angažmani (tržišne ponude) elektrana;
— raspoloživost grana i generatora,
— predviđanje raspodjele opterećenja i
— regionalna bilanca snage.

4 TRANSMISSION NETWORK PLANNING UNCERTAINTIES

Besides the above mentioned input data, other significant uncertainties in the network planning process have appeared due to a deregulated market environment. The most important uncertainties for the SEE region with respect to the transmission system development have been identified in [3]. They are:

— new power plants sizes and locations,
— hydrological conditions,
— generators bids,
— branches and generators availability,
— load prediction, and
— regional power balance.

Scenariji planiranja prijenosne mreže analizirani u sklopu ove studije odnose se na:

- ažurirane rezultate GIS-a za 1., 2. i 8. scenarij (GIS sc1, GIS sc2, GIS sc8),
- hidrološke uvjete (suho, vlažno),
- raspoloživost grana (n raspoloživih grana, (n – 1) raspoloživih grana), i
- regionalnu bilancu snage (uvoz, izvoz, uravnotežena bilanca - za države GIS-a).

Scenariji planiranja prijenosne mreže koji se temelje na tri scenarija iz ažuriranog GIS-a prikazani su na slici 6 i u tablici 4.

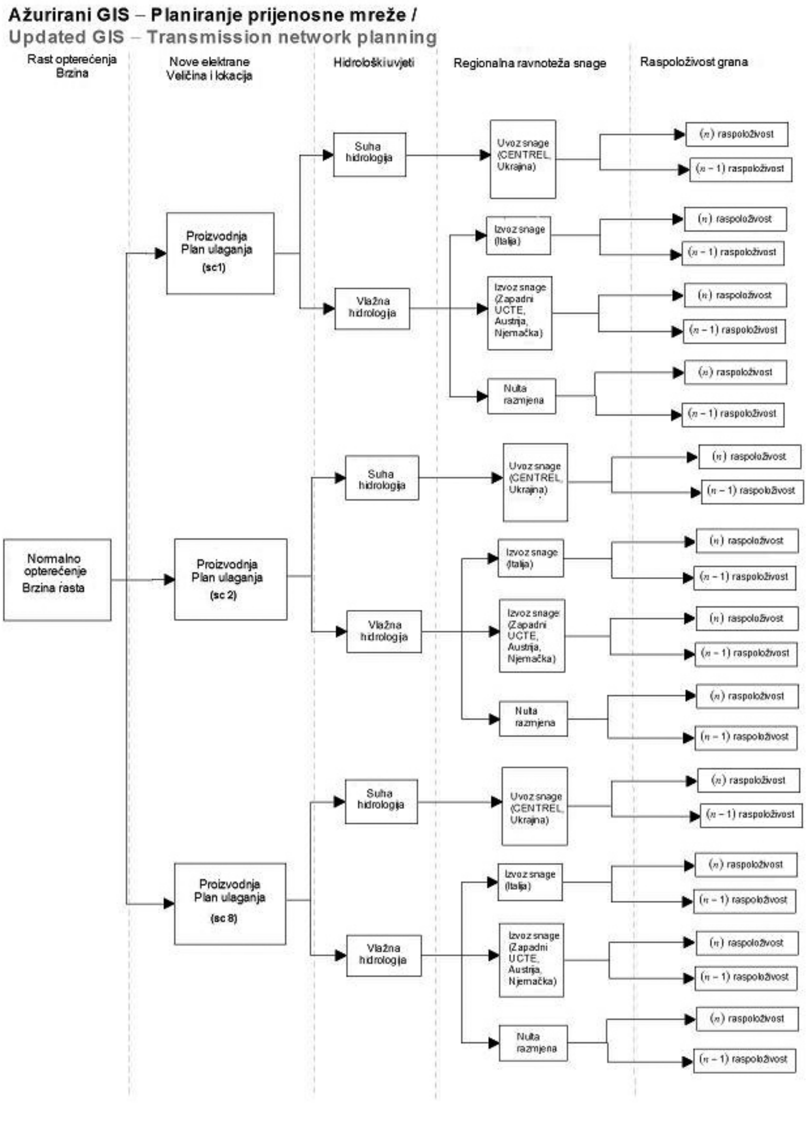
Na temelju postojeće situacije i odgovarajućih predviđanja pretpostavljeno je da su najvjerojatniji smjerovi izvoza električne energije prema Italiji i zapadnim zemljama UCTE-a (Njemačka, Austrija), dok smjerovi uvoza vode iz CENTREL-a i Ukrajine.

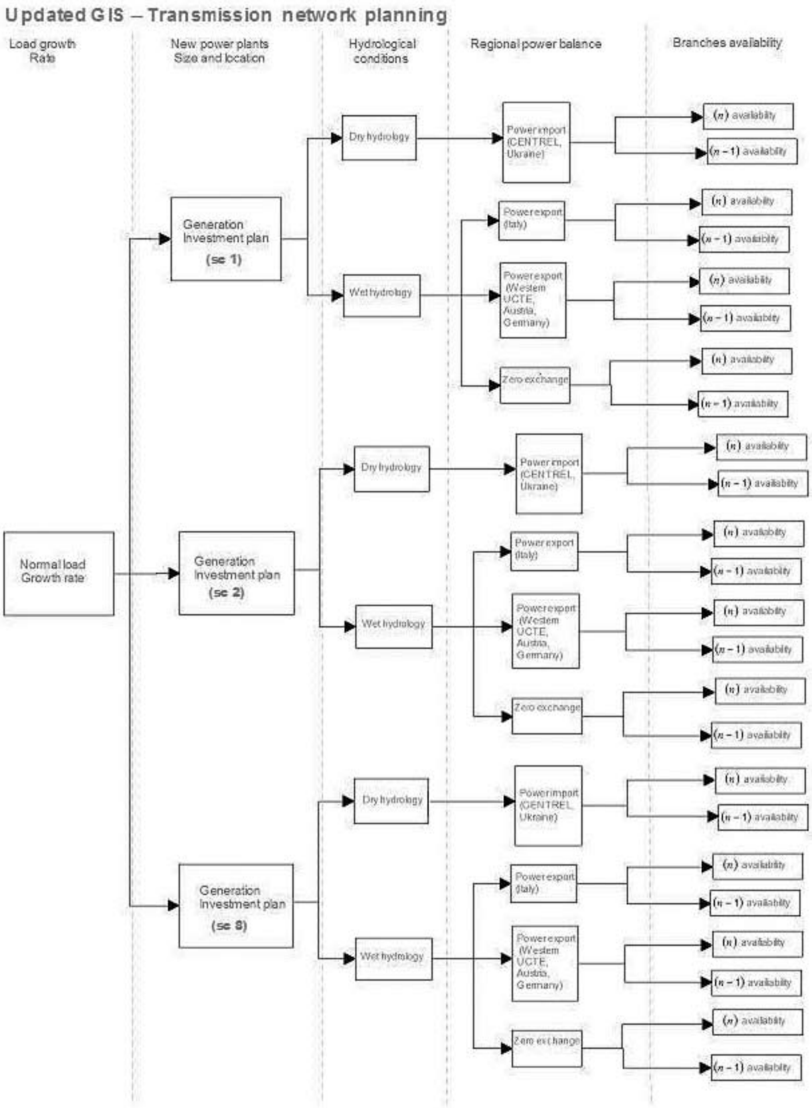
Within this study transmission network planning scenarios were related to:

- updated GIS results for scenarios 1, 2 and 8 (GIS sc1, GIS sc2, GIS sc8),
- hydrological conditions (dry, wet),
- branches availability (n available branches, (n – 1) available branches), and
- regional power balance (import, export, zero balance – related to the GIS countries).

Transmission planning scenarios based on the three scenarios from the updated GIS are presented in Figure 6 and Table 4.

It is assumed, based on the existing situation and related predictions, that the most probable export paths lead to Italy and western UCTE countries (Germany, Austria), and import paths from CENTREL and Ukraine.





Slika 6 — Scenariji planiranja prijenosne mreže

Figure 6 — Transmission network planning scenarios

Tablica 4 – Scenariji planiranja prijenosne mreže

Table 4 – Transmission network planning scenarios

Scenarij GIS / GIS scenario	**Hidrologija / Hydrology**	**Regionalna ravnoteža / Regional balance**	**Identifikacija / Identification**
Osnovni scenarij sa službenim programom revitalizacije (sc1) / Base case with official rehabilitation program (sc1)	Suha / Dry	Uvoz (CENTREL, Ukrajina) / Import (CENTREL, Ukraine)	sc1 - 1
	Vlažna / Wet	Izvoz u Italiju / Export to Italy	sc1 - 2
		Izvoz u zapadni UCTE (Njemačka, Austrija) / Export to Western UCTE (Germany, Austria)	sc1 - 3
		Nulta ravnoteža / Zero Balance	sc1 - 4
Osnovni scenarij s ekonomski opravdanim prgramom revitalizacije (sc2) / Base case with justified rehabilitation program (sc2)	Suha / Dry	Uvoz (CENTREL, Ukrajina) / Import (CENTREL, Ukraine)	sc2 – 1
	Vlažna / Wet	Izvoz u Italiju / Export to Italy	sc2 - 2
		Izvoz u zapadni UCTE (Njemačka, Austrija) / Export to Western UCTE (Germany, Austria)	sc2 - 3
		Nulta ravnoteža / Zero Balance	sc2 - 4
Scenarij hidroelektrana i visoke cijene goriva (sc8) / Hydro power plants and high fuel price scenario (sc8)	Suha / Dry	Uvoz (CENTREL, Ukrajina) / Import (CENTREL, Ukraine)	sc8 - 1
	Vlažna / Wet	Izvoz u Italiju / Export to Italy	sc8 - 2
		Izvoz u zapadni UCTE (Njemačka, Austrija) / Export to Western UCTE (Germany, Austria)	sc8 - 3
		Nulta ravnoteža / Zero Balance	sc8 - 4

5 KRITERIJI PLANIRANJA PRIJENOSNE MREŽE I METODOLOGIJA ZA PROIRITIZACIJU PROJEKATA

Kako je ranije navedeno, u okviru radne grupe SECI za planiranje regionalne prijenosne mreže izrađena je studija pod nazivom *Transmission Network Investment Criteria* [3], s ciljem definiranja kriterija ulaganja u prijenosnu mrežu iz regionalne perspektive i ujednačavanja metodologije za prioritizaciju projekata u regiji. U studiji ažuriranog GIS-a projekti - kandidati za izgradnju prijenosne mreže vrjednovali su se na temelju kriterija i metodologije prioritizacije detaljno razrađenim u prethodno navedenoj studiji.

5.1. Kriteriji za prioritizaciju projekata

Kriteriji planiranja razvoja prijenosne mreže dijele se na tehničke i ekonomske kriterije. Zbog (ne)raspoloživosti odgovarajućih softverskih alata i ulaznih podataka predložena je odvojena primjena tehničkih i ekonomskih kriterija za vrjednovanje projekata prijenosne mreže i prioritizacije projekata. Naime, operatori prijenosnog sustava u jugoistočnoj Europi trenutačno su opremljeni i osposobljeni samo za uporabu tehničkih kriterija.

Općenito, tehnički kriteriji za planiranje razvoja prijenosne mreže jugoistočne Europe korišteni za tehničko vrjednovanje projekata - kandidata za pojačanje prijenosne mreže uključuju:

- $(n-1)$ kriterij sigurnosti,
- kriterij napona i reaktivne snage,
- kriterij kratkog spoja, i
- kriterij stabilnosti.

Za dugoročno planiranje prijenosne mreže provedeno u predmetnoj studiji primijenjen je samo $(n-1)$ kriterij sigurnosti.

Ekonomski kriterij za planiranje razvoja prijenosne mreže vezan je uz indeks profitabilnosti. Indeks profitabilnosti odnosi se na omjer između očekivane godišnje dobiti izgradnjom promatranog kandidata i očekivanih troškova njegove izgradnje i pogona na godišnjoj razini. Projekti - kandidati smatraju se ekonomski profitabilnima ukoliko je njihov indeks profitabilnosti veći od 1 unutar razmatranog razdoblja. Pri ekonomskom vrjednovanju koristi od izgradnje projekata – kandidata mogu se podijeliti na:

- korist od smanjenja očekivanih godišnjih troškova neisporučene električne energije,
- korist od smanjenja godišnjih gubitaka,
- korist od smanjenja godišnjih troškova preraspodjele proizvodnje (eng. re-dispatching), i

5 TRANSMISSION NETWORK PLANNING CRITERIA AND METHODOLOGY FOR PROJECT PRIORITIZATION

The SECI (South East Europe Cooperative Initiative) Project Group on the Regional Transmission System Planning prepared the study entitled Transmission Network Investment Criteria [3], with the aim to define transmission investment criteria from the regional perspective and uniform methodology for project prioritization. In this study, candidate transmission projects have to be evaluated by using predefined regional investment criteria and predefined prioritization methodology developed in the aforementioned study.

5.1 Criteria for prioritization of candidate projects

The transmission system planning criteria are divided into technical and economic criteria. Separate application of technical and economic criteria in transmission system development evaluation and projects prioritization is suggested here concerning the availability of appropriate software tools and input data. SEE TSOs are currently equipped and trained to use technical criteria only.

Technical criteria for SEE transmission system planning are used for the technical evaluation of the candidate projects for transmission network reinforcements. Technical criteria include:

- security $(n-1)$ criterion,
- voltage and reactive power criterion,
- short-circuit criterion, and
- stability criterion.

For the long term planning, such as in this study, only the security $(n-1)$ criterion was used.

The economic criterion for transmission system planning is related to the profitability index. The profitability index is defined as the ratio between expected annual benefit from the candidate project and the annuity of its expected costs. The candidate project is economically profitable if its profitability index is larger than 1 within the planning period. The following types of benefit from construction of candidate projects may be estimated for the purpose of economic evaluation:

- benefit due to reduction of expected annual undelivered electricity costs,
- benefit due to annual losses reduction,
- benefit due to reduction of annual re-dispatching costs, and

- korist od smanjenja godišnjih troškova zagušenja.

U svrhu ekonomskog vrjednovanja, vrste troškova od izgradnje projekata kandidata mogu se podijeliti na sljedeći način:

- troškovi ulaganja, i
- troškovi pogona i troškovi održavanja

5.2. Metodologija za prioritizaciju projekata

Vrjednovani su samo projekti – kandidati koji bi mogli biti od regionalnog značenja, dok su u polaznu topologiju mreže uključeni i neki projekti od lokalnog značenja, koje su imenovali pojedini operatori sustava.

Proračun tokova snaga i analiza sigurnosti izvršeni su za sve scenarije planiranja te su zabilježena uočena ograničenja. Popis zabilježenih ograničenja za sve proučene scenarije planiranja u promatranom razdoblju činili su osnovu za tehnička vrjednovanja o kojima se govori u nastavku.

Počevši od zajedničke liste projekata – kandidata, koje operatori prijenosnog sustava jugoistočne Europe označavaju kao projekte od mogućeg regionalnog značenja, i provedene analize tokova snaga i $(n-1)$ analize sigurnosti, projekti – kandidati su jedan po jedan uključivani u polaznu topologiju mreže, nakon čega je provedena nova analiza tokova snaga i sigurnosti za sve analizirane scenarije planiranja u razmatranom razdoblju. Izrađen je novi popis uočenih ograničenja, a naglašena su ona ograničenja koja su uklonjena nakon što je novi projekt uključen u topologiju mreže.

Projekti - kandidati tehnički su prioritizirani prema ograničenjima mreže koja su uklonjena uvođenjem projekata kandidata i to na slijedeći način:

- prva grupa sadrži projekte - kandidate koji uklanjaju ograničenja u mreži s (n) raspoloživih grana (najviši stupanj tehničke prioritizacije), i
- druga grupa sadrži projekte koji uklanjaju ograničenja u mreži s $(n-1)$ raspoloživih grana (niži stupanj tehničke prioritizacije).

Unutar te dvije grupe projekata kandidata izvršena je daljnja tehnička prioritizacija prema:

- broju scenarija planiranja u kojima projekt - kandidat uklanja ograničenja u mreži (što je uklonjeno više scenarija planiranja s ograničenjima u mreži, to je projekt tehnički značajniji),

- benefit due to annual congestion costs reduction.

The following types of candidate project construction costs may be estimated for the purpose of the economic evaluation:

- investment costs, and
- operation and maintenance costs.

5.2 Methodology for prioritization of candidate projects

Only candidate projects with possible regional significance were evaluated at the SEE regional level, while transmission projects with local significance, nominated by the TSOs, were included in the base case network topology.

Load flow and security analysis were performed for all planning scenarios and network constraints were recorded. A list of recorded network constraints for all analyzed planning scenarios in the studied year was the basis for the candidate projects' technical and economical evaluations that follow.

Starting from the common list of candidate projects, nominated by the SEE TSOs as projects with possible regional significance, and the conducted analyses of load flows and security $(n-1)$ analysis, candidate projects were included into the network topology one by one, and new load flow and security analysis was performed for all the analyzed planning scenarios in a studied year. A new list of network constraints was created, and constraints which are removed when a new project is included into network topology were highlighted.

Candidate projects which are included in the reviewed list of candidate projects are technically prioritized according to network constraints which are removed by candidate projects:

- the first group contains candidate projects that remove network constraints with (n) available branches (the highest level of technical prioritization), and
- the second group contains projects that remove network constraints with $(n-1)$ available branches (lower level of technical prioritization).

Inside these two groups of candidate projects, further technical prioritization was made according to:

- the number of planning scenarios in which candidate project removes network constraints (more planning scenarios with network constraints that are removed by candidate project, more technically significant is a project),
- voltage level of overloaded transmission lines

- naponskoj razini preopterećenih dalekovoda (uklanjanje preopterećenja na 400 kV razini je značajnije od onoga na 220 kV naponskoj razini), i
- broju ograničenja u mreži koje uklanja projekt - kandidat (što je uklonjeno više ograničenja, to je projekt tehnički značajniji).

Projekti - kandidati prioritizirani prema tehničkim kriterijima trebali bi se podvrgnuti daljnjem vrjednovanju i prioritizaciji prema ekonomskim kriterijima koji se temelje padajućem nizu indeksa profitabilnosti.

6. MODEL ELEKTROENERGETSKOG SUSTAVA

Za potrebe ove analize korišten je PSS/E model regionalnog elektroenergetskog sustava s više od 6000 sabirnica, a kojeg je priredila Radna grupa SECI za planiranje regionalne prijenosne mreže, čiji je pokrovitelj USAID već duži niz godina [5]. Model elektroenergetskog sustava prilagođen je ažuriranoj verziji GIS-a, a obuhvaća topologiju mreže, opterećenje, proizvodnju i razmjene snaga. Uz sudjelovanje svih operatora sustava i planera prijenosne mreže iz jugoistočne Europe, ova Radna grupa finalizirala je PSS/E model regionalnog prijenosnog sustava za 2010. i 2015. godinu koji je pogodan za ovu analizu. Osim država obuhvaćenih GIS-om, ovaj regionalni model također obuhvaća modele Grčke, Turske, Slovenije, Burstyna (Ukrajina), Italije, Mađarske i Austrije. U model je uključena visokonaponska prijenosna mreža 750 kV, 220 kV, 150 kV, 220 kV (koja postoji u Grčkoj i Turskoj) i 110 kV naponske razine. Osim toga, sve nove transformatorske stanice i vodovi za koje se očekuje da će biti u pogonu do 2015. godine (prema planovima razvoja pojedinih zemalja) također su uključene u model. Analize na ovakvom PSS/E modelu omogućile su vjerodostojan uvid u adekvatnost prijenosne mreže, odnosno pomoću njih je bilo moguće odrediti koja prioritetna pojačanja u prijenosnoj mreži je potrebno realizirati kako bi se ispunili zahtjevi proizvodnje iz ažuriranog GIS-a za 2015. godinu pod normalnim i izvanrednim $(n-1)$ pogonskim uvjetima.

Sve proizvodne jedinice koje su priključene na prijenosnu mrežu modelirane su prema stvarnom stanju (s blok-transformatorima). Planirane proizvodne jedinice (prema ažuriranoj verziji GIS-a) modelirane su na temelju raspoloživih podataka: preko blok-transformatorima ili s direktnim priključkom na sabirnice. Model je definiran za proračun i analizu tokova snaga, ali s odgovarajućim unošenjem podataka (što je već razvijeno i testirano) može biti korišten također i za ostale vrste analiza:

(removal of overloading on 400 kV level is more significant than on 220 kV), and
- the number of network constraints that are removed by a candidate project (the more constraints are removed, the more technically significant is a project).

Candidate projects which are included in the reviewed list of candidate projects and prioritized according to the technical criteria should be further evaluated and prioritized according to the economic criteria based on the highest profitability indexes.

6 POWER SYSTEM MODEL

PSS/E Regional Transmission System Model which was created by the SECI Project Group on the Regional Transmission System Planning, sponsored by USAID, was used for these analyses with more than 6000 buses [5]. The power system model was adjusted to the updated GIS concerning network topology, demand, production and exchange data. With a participation of all power system utilities and planners from South East Europe, the Project Group finalized the PSS/E Regional Transmission System Model for 2010 and 2015 suitable for this analysis. Besides the GIS countries, the RTSM also comprises models of Greece, Turkey, Slovenia, Burstyn (Ukraine), Italy, Hungary and Austria, with the aim to have adequate network representation for all types of network analyses. High voltage transmission network of 750 kV, 220 kV, 150 kV, 220 kV (existing in Greece and Turkey), and 110 kV voltage levels is implemented in the model. Moreover, all new substations and lines which are expected to be operational till 2015 (according to the long term development plans) are modeled as well. Analyses of the PSS/E RTSM provided insight in transmission network adequacy and determined what transmission reinforcements or additional priorities are eventually required to meet the updated GIS 2015 generation dispatch under normal and $(n-1)$ operating conditions.

All generation units that are connected to the transmission voltage level were modeled as they are in reality (with step-up transformers). Planned generation units (according to the update of the GIS) were modeled with step-up transformers or as plant bus injections on the basis of available data. The model was designed for load-flow calculations and analysis, but with the adequate data input (already developed and tested) it can be used for the other types of analysis as well:

- short-circuit calculations, and
- dynamics (transient stability assessment).

Each interconnection line has assigned an X node

- proračune kratkog spoja, i
- dinamičke analize.

Svakom je interkonektivnom vodu dodijeljen tzv. X čvor koji je lociran točno na granici svake države (a ne u sredini interkonektivnog voda).
Dopuštene razine napona prikazane su u tablici 5. Ova ograničenja korištena su i prilikom proračuna tokova snaga, kao i pri analizi sigurnosti.

which is placed at the border of each country (not in the middle of the tie line).
Voltage level limits are presented in the Table 5. These limits are used in load flow calculations as well as in the contingency analysis.

Tablica 5 – Definirana ograničenja za naponske razine
Table 5 – Defined limits for voltage levels

	Definirane naponske razine / Defined voltage levels											
	750 kV		400 kV		220 kV		150 kV		110 kV		Generator / Generator	
	min	max	min	max	min	max	Min	max	min	Max	min	max
kV	712	787	380	420	198	242	135	165	99	121		
p.u.	0,95	1,05	0,95	1,05	0,90	1,10	0,90	1,10	0,90	1,10	0,95	1,05

Navedena ograničenja definirana su prema pogonskim i planerskim standardima koji se koriste u regiji. Iako su u interventnim slučajevima dozvoljena i veća odstupanja napona, ona ovdje nisu uzeta u obzir.

Popis elemenata korištenih u analizi sigurnosti sadržavao je:

- sve 400 kV i 220 kV interkonektivne vodove,
- sve 400 kV i 220 kV interne vodove, osim vodova čiji ispad uzrokuje otočni pogon, i
- sve 400/220 kV transformatore (u slučaju paralelnih transformatora razmatran je ispad jednog transformatora).

Vodovi od 110 kV smatraju se od lokalnog značaja, pa nisu evaluirani u analizi sigurnosti.

Za vodove i transformatore korištene su postojeće termičke (strujne) granice opterećenja. Te granice definirane su na temelju temperature do koje se vodič zagrije uslijed protoka struje. U ovim analizama struja vodiča ne smije premašiti termičku granicu, koja se određuje ovisno o materijalu i presjeku vodiča prema standardu IEC (50) 466: 1995 – *International Electrotechnical Vocabulary* - Chapter 466: Overhead Lines. Za termičku granicu opterećenja transformatora uzeta je pripadna instalirana snaga. Svaki element opterećen iznad termičke granice smatra se preopterećenim.

Sva stanja sustava u kojima je iznos napona izvan dozvoljenih granica, ili su grane opterećene iznad termičke granice (preopterećene) pri analizi potpune raspoloživosti ili $(n-1)$ analizi, smatraju se nesigurnim stanjima i kao takva su prikazana u ovoj studiji.

These limits are defined according to the operational and planning standards used in the monitored region, and they are used for full topology and $(n-1)$ analyses. Although wider voltage limits are allowed in emergency conditions for some voltage levels, these are not taken into consideration.

The list of contingencies included:

- all interconnection 400 kV and 220 kV lines,
- all internal 400 kV and 220 kV lines, except the lines which outage causes island operation, and
- all transformers 400/220 kV (in case of parallel transformers, outage of one transformer is considered).

110 kV lines were taken as of local importance.

Current thermal limits are used as rated limits for lines and transformers. These limits are established on the basis of a temperature to which the conductor is heated by the current above which either the conductor material would start being softened or the clearance from conductor to ground would drop beyond permitted limits. In these analyses, conductor current must not reach limits imposed by thermal limit defined for conductors material and cross-section according to the IEC standard (50) 466: 1995 – International Electrotechnical Vocabulary - Chapter 466: Overhead Lines. For transformers, installed rated MVA power is used as thermal limit. Every branch with a current above its thermal limit is treated as overloaded.

All system states in which voltage level is outside permitted limits or branches are loaded beyond thermal limit (overloaded), by full topology or $(n-1)$ contingency analyses, are treated as insecure states and referenced as such in the present study.

Tablica 6 i slika 7 prikazuju postojeće interkonektivne vodove u jugoistočnoj Europi (2008.), kao i one vodove koji su bili u izgradnji tijekom izrade ove studije. Ova topologija je nadograđena za 2015. godinu nekolicinom planiranih interkonektivnih vodova. Planirani interkonektivni vodovi za koje se smatra da će sigurno postojati u 2015. godini prikazani su u tablici 7 i na slici 8. Na temelju informacija prikupljenih od susjednih operatora prijenosnog sustava i UCTE System Adequacy Forecast-a bilo je moguće odrediti godinu planiranog puštanja u pogon svakog voda s navedenog popisa. Svi pretpostavljeni dalekovodi omogućuju značajno jačanje postojeće prijenosne mreže u jugoistočnoj Europi. Pretpostavljeno je da će podmorski HVDC kabel 400 kV Arachtos (GR) – Galatina (IT) biti u pogonu 2015. godine s opterećenjem u iznosu od 400 MW iz smjera Grčke prema Italiji.

Dalekovodi 400 kV S. Mitrovica (RS) – Ugljevik (BA) i Bitola (MK) – Florina (GR) uzeti su kao planirani dalekovodi u originalnom GIS-u, ali tijekom razdoblja između originalne i ažurirane verzije GIS-a, ti su vodovi realizirani (izgradnja i puštanje u pogon su završeni). Osim toga, 400 MW DV Kashar – Durres i Kashar - Elbasan (Albanija) smatraju se pojačanjem interne mreže nužnim preduvjetom za realizaciju nekih drugih kandidata. Iako 220 kV DV Kashar – Durres već postoji, TS 400/220 kV u Durresu nije modelirana kako bi se spriječio nepotreban paralelni tok snage kroz 400 kV i 220 kV mrežu. Također, pretpostavljeno je da će interkonektivni vodovi 400 kV Isaccea (RO) – Vulcanesti (MD) i 750 kV Zahidoukrainskaya (UA)–Isaccea (RO) biti izvan pogona.

ble 6 and Figure 7 show existing interconnection lines in the SEE (2008), as well as the lines that were under construction at the moment of the study analysis. This topology is upgraded for 2015 by adding several planned interconnection lines. Planned interconnection lines which were considered as definitely present in 2015 are given in Table 7 and in Figure 8. Based on the information collected from the neighboring TSOs and UCTE System Adequacy Forecast it was possible to determine the years of planned commissioning for each OHL from the list. All these assumed transmission lines provide a substantial reinforcement to the actual transmission network of the SEE region. The submarine HVDC cable 400 kV Arachtos (GR) – Galatina (IT) is considered to be in operation in 2015 with the set direction of power flow of 400 MW from Greece to Italy.

Transmission lines 400 kV S. Mitrovica (RS) – Ugljevik (BA) and Bitola (MK) – Florina (GR) were treated as planned transmission lines in the original GIS, but during the period from the original GIS to the update of the GIS, these lines became actual (construction and erection were completed). Other than that, OHLs 400 MW Kashar – Durres and Kashar - Elbasan (Albania) were treated as necessary internal grid reinforcement, for inclusion of further transmission line candidates. Although, OHL 220 kV Kashar – Durres already exists, transformation 400/220 kV in Durres is not modeled in order to avoid unnecessary parallel flow through 400 kV and 220 kV grid. Tie lines 400 kV Issacea (RO) – Vulcanesti (MD) and 750 kV Zahidoukrainskaya (UA)–Isaccea (RO) were considered to be out of operation.

*DV 220 kV Mraclin – Prijedor je privremeno bio izvan pogona do 2009. /
*OHL 220 kV Mraclin – Prijedor was temporary out of operation till 2009

Slika 7 — Interkonekcijski vodovi u Jugoistočnoj Europi u 2008.
Figure 7 — Interconnection lines in South East Europe in 2008

Tablica 6 – Popis interkonektivnih vodova u Jugoistočnoj Europi u 2008. godini
Table 6 – List of interconnection lines in South East Europe in 2008

Interkonekcijski vod / Interconnection line	Povezane države / Interconnected countries	Naponska razina / Voltage level,	Vodiči / Conductors			Prijenosna moć / Transfer capacity,	Duljina / Lenght, km		
		kV	Tip / Type	Veličina / Size, mm²	Broj po fazi / Number per phase	MVA	Do granice / I to border	Od granice/ Border to II	Ukupno / Total
Varna – Isaccea	BG – RO	750	ACSR	300	5	2 390	150	85	235
Albertirsa – Zapadoukrainska	HU – UA	750	ACSR	400	5	5 360	268	254	522
Isaccea – Pivdenoukrainska	RO – UA	750	ACSR	400	5	5 360	5	395	400
God – Levice	HU – SK	400	ACSR	500/350	2/3	1 440	88	36	124
Gyor – Gabcikovo	HU – SK	400	ACSR	500/450	2/3	1 440	29	15	44
Zemlak – Kardia	AL – GR	400	ACSR	500	2	1 309	21	80	101
Mostar 4 – Konjsko	BA – HR	400	ACSR	490	2	1 318	41	69	110
Ugljevik – Ernestinovo	BA – HR	400	ACSR	490	2	1 318	39	53	92
Blagoevgrad – Thessaloniki	BG – GR	400	ACSR	500	2	1 309	72	102	174
Dobrudja – Isaccea	BG – RO	400	ACSR	400	3	1 715	81	150	231
Matitsa Istok – Hamitabat	BG – TR	400	ACSR	400	3	1 715	59	90	149
Isaccea – Vulcanesti	RO – MOLD	400	ACSR	400	3	1 715	5	54	59
Kozloduy – Tantareni (dvostruki / double)	BG – RO	400	ACSR	500/300	2/3	2 490	14	102	116
Sofia West – Niš	Bg – RS	400	ACSR	500	2	1 330	37	86	123
Maritsa Istok – Babaeski	BG – TR	400	ACSR	500	2	1 309	50	77	127
Žerjavinec – Heviz (dvostruki / double)	HR – HU	400	ACSR	490	2	1 318	99	69	168
Dubrovo ACSR Thesaloniki	MK – GR	400	ACSR	490	2	1 330	55	60	115
Skopje – Kosovo B	MK – RS	400	ACSR	490	2	1 330	36	68	104
Arachtos – Galatina HVDC	GR – IT	400	ACSR	1 250	–	500	–	–	313
Gyor – Wien Sud (dvostruki / double)	HU – AT	400	ACSR	500	2	2 563	59	63	122
Podgorica – Trebinje	ME – BA	400	ACSR	490	2	1 330	60	21	81
Arad – Sandorfalva	RO – HU	400	ACSR	450/500	2	1 212	5	52	57
Portile De Fier – Djerdap	RS – RO	400	ACSR	967	2	1 330	1	2	3
Rosiori – Mukachevo	RO – UA	400	ACSR	450	2	1 212	39	36	75
Ernestinovo – S. Mitrovica	HR – RS	400	ACSR	490	2	1 330	52	41	93
Subotica – Sandorfalva	RS – HU	400	ACSR	490	2	1 330	27	21	48
Maribor – Keinachtal (dvostruki / double)	SI – AT	400	ACSR	490	2	1 330	26	37	63
Melina – Divača	HR – SI	400	ACSR	490	2	1 318	26	41	67
Tumbri – Krško (dvostruki / double)	HR – SI	400	ACSR	490	2	1 318	32	16	48
Divača – Radipuglia	SI – IT	400	ACSR	490	2	1 330	39	10	49
Mukachevo – Sajoszeged	UA – HU	400	ACSR	400	2	1 386	8	142	150
Bitola – Florina	MK – GR	400	ACSR	490	2	1 312	20	13	33
Ribarevine – Kosovo B	RS – ME	400	ACSR	490	2	2 000	50	73	123
Ugljevik – S. Mitrovica	BA – RS	400	ACSR	490	2	1 920	46	34	80
Vau Dejes – Podgorica	AL – ME	220	ACSR	360	1	301	47	21	68
Fierze – Prizren	AL – RS	220	ACSR	360	1	301	26	45	71
Plevlja – Bajina Bašta	ME – RS	220	ACSR	360	1	720	15	82	97
Plevlja – Požega	ME – RS	220	ACSR	360	1	1 000	14	78	92
Gradačac – Djakovo	BA – HR	220	ACSR	360	1	300	19	27	46
Prijedor – Mraclin	BA – HR	220	ACSR	360	1	300	–	66	68
Mostar 4 – Zakučac	BA – HR	220	ACSR	360	1	300	49	50	99
Prijedor 2 – Međurić	BA – HR	220	ACSR	360	1	300	34	32	66
TE / TPP Tuzla – Đakovo	BA – HR	220	ACSR	360	1	300	65	27	92
Trebinje – HE / HPP Dubrovnik (Plat) (dvoatruki /double)	BA – HR	220	ACSR	240	2	491	7	5	12
Trebinje – HE / HPP Perućica	BA – ME	220	ACSR	360	1	301	20	42	62
Sarajevo 20 – Piva	BA – ME	220	ACSR	490	2/1	366	61	23	84
Višegrad – Požega	BA – RS	220	ACSR	360	1	301	18	51	69
Žerjavinec – Cirkovce	HR – SI	220	ACSR	360	1	300	19	51	70
Skopje – Kosovo A (dvostruki/ double)	MK – RS	220	ACSR	360	1	301	18	65	83
Gyor – Wien Sud	HU – AT	220	ACSR	360	1	305	59	63	122
Gyor – Neusiedl	HU – AT	220	ACSR	360	1	305	55	27	82
Podlog – Obersielach	SI – AT	220	ACSR	490	1	366	46	20	66
Pehlin – Divača	HR – SI	220	ACSR	490	1	350	6	47	53
Divača – Padricano	SI – IT	220	ACSR	490	1	366	10	2	12
Mukachevo – Kisvarda	UA – HU	220	ACSR	400	1	308	54	10	64
Mukachevo – Tiszalok	UA – HU	220	ACSR	400	1	308	97	35	132

Tablica 7 – Popis prijenosnih vodova za koje se pretpostavlja da će biti pušteni u pogon u jugoistočnoj Europi do 2015.
Table 7 – List of transmission lines considered to be in operation in the SEE region until 2015

Vrsta elementa / Type of element	Napon / Voltage, V	Od / From	Do / To	Vodiči / Conductors			Ukupna dužina / Total legth	Prijenosna moć / Transfer capacity
				Vrsta / Type	Veličina / Size, mm^2	Broj po fazi / Number per phase	km	MVA
DV / OHL	400	Štip (MK)	Chervena Mogila (BU)	ACSR	490	2	146	1 420
DV / OHL	400	Podgorica (ME)	Kashar (AL)	ACSR	490	2	144,2	1 350
DV / OHL	400	N. Santa (GR)	Babaeski (TR)	ACSR	490	3	180	1 500
DV / OHL	400	Niš–Leskovac–Vranje (RS)	Skopje 1 (MK)	ACSR	490	2	95	1 330
DV / OHL	400	Bekescsaba (HU)	Nadab (RO)	ACSR	500/300	2/3	54	1 211
DV / OHL (dvostruki / double)	400	Okroglo (SI)	Udine (IT)	ACSR	400	2	113	1 163
DV / OHL	400	Sajovanka (HU)	Rimavska Sobota (SK)	ACSR	500	1	40	554,3
DV / OHL	400	Imotski (HR)	Rama (BiH)	ACSR	360	1	75	300

* Umjesto čvora Imotski 220 kV može postojati drugi unutarnji čvor u Hrvatskoj koji neće promijeniti rezultate studije / Instead of the node Imotski 220 kV there can be another internal node in Croatia that will not change the study results.

Slika 8 — Planirani kandidati za interkonekcijske vodove i pretpostavljeni interkonekcijski vodovi u 2015.
Figure 8 — Planned interconnection line candidates and presumed interconnection lines in 2015

Osim vodova iz tablice 7, ispitana je još jedna grupa kandidata. Ti kandidati – interkonektivni vodovi do 2015. prikazani su u tablici 8. Iako riječ „kandidat" može upućivati na to da se razmatra samo jedan dalekovod, to se odnosi i na grupu vodova koji će implicitno biti zajedno stavljeni u pogon. U nekim slučajevima, skupina od dva ili tri elementa (DV ili kabel) predstavljaju jednog kandidata (npr., kandidat br.6, 400 kV DV Bitola – Elbasan i 400 kV HVDC Durres – Foggia).

Osim toga, u međuvremenu su neki od projekata kandidata za izgradnju vodova uključeni u službene planove razvoja ili je njihova izgradnja već započela (npr. Ernestinovo (HR) – Pecs (HU), dok su se u svojstvu kandidata pojavile neke nove opcije (npr. Tivat (MN) – Foggia (IT).

Besides the lines given in Table 7, another group of transmission line candidates was investigated, one by one. These planned interconnection line candidates in South East Europe until 2015 are shown in Table 8. Although the term candidate may mean that only one transmission line is under consideration, the present study considers candidates to be even a group of elements which are implicitly going to be put in operation together. In some cases, a group of two or three elements (OHL or cable) represent one transmission candidate for analysis (i.e. candidate 6, OHL 400 kV Bitola – Elbasan and HVDC 400 kV Durres – Foggia).

Also, in the meantime, some of the candidate line projects were included in the official development plans or even started with construction (i.e. Ernestinovo (HR) – Pecs (HU), while some new lines appeared to be candidates (i.e. Tivat (MN) – Foggia (IT).

Tablica 8 – Popis projekata - kandidata u prijenosnoj mreži jugoistočne Europe do 2015.
Table 8 – List of transmission line candidates for operation in the SEE region until 2015

Kandidat br. / Candidate No	Vrsta elementa / Type of element	Napon / Voltage, V	Od / From	Do / To	Vodiči / Conductors			Ukupna dužina / Total legth	Prijenosna moć / Transfer capacity
					Vrsta / Type	Veličina / Size, mm²	Broj po fazi / Number per phase	km	MVA
1	DV / OHL	400	Kashar (AL)	Kosovo B (UNMIK)	ACSR	490	2	240	1 330
2	DV / OHL	400	N. Santa (GR)	Maritsa Istok 1 (BU)	ACSR	490	3	180	1 715
3	DV / OHL (dvostruki / double)	400	Ernestinovo (HR)	Pecs (HU)	ACSR	490/500	2	87	2x1 330
4	DV / OHL	400	Žerjavinec (HR)	Heviz (HU)	ACSR	490	2	181	1 386
	DV / OHL	400	Heviz (HU)	Cirkovce (SI)	ACSR	490	2	162	1 386
	DV / OHL	400	Cirkovce (SI)	Žerjavinec (HR)	ACSR	490	2	140	1 386
5	DV / OHL	400	Novi Sad (RS)	Timisoara (RO)	ACSR	490	2	128	1 330
6	DV / OHL	400	Bitola 2 (MK)	Elbasan (AL)	ACSR	490	2	125	1 330
	HV DC	400	Durres (AL)	Foggia (IT)	DC cable	1 250	–	250	500
7	HV DC	400	Konjsko (HR)	Candia (IT)	DC cable	1 250	–	200	500
8	DV / OHL	400	Ernestinovo (HR)	Pecs (HU)	ACSR	490/500	2	87	1 330
	DV / OHL	400	Pecs (HU)	Sombor (RS)	ACSR	500/490	2	115	1 330
	DV / OHL	400	Ernestinovo (HR)	Sombor (RS)	ACSR	490	2	115	1 330

U nastavku se navode komentari o pojedinim projektima - kandidatima za izgradnju:

- **Interkonektivni vod 400 kV Kashar (AL) – Kosovo B (KS):**

Ovaj interkonektivni vod trebao bi povećati stabilnost sustava, sigurnost i prijenosnu moć između sjevernog i južnog dijela Albanije te između Albanije i Kosova. Najznačajniji utjecaj bi trebao imati na naponske prilike na jugu Albanije. Drugi cilj ove interkonekcije je evakuacija velike snage elektrana koje se planiraju izgraditi na Kosovu do 2020.

- **Interkonektivni vod 400 kV Nea Santa (GR) – Maritsa East 1 (BG):**

Analizirano je više verzija novog povezivanja Bugarske i Grčke, a ovaj kandidat predstavlja posljednju razmatranu varijantu. Očekuje se da će ovaj vod ne samo povećati prijenosnu moć između Bugarske i Grčke, već da će povećati sigurnost i stabilnost elektroenergetskog sustava u smislu budućeg povezivanja Turske s UCTE-om,

Comments for transmission line candidates:

- **Interconnection line 400 kV Kashar (AL) – Kosovo B (KS):**

This tie line should increase system stability, security and transmission capacity between the north and the south region of Albania and between Albania and Kosovo. The most significant impact should be on the voltage profile in the Albanian consumption area in the south. Another future purpose of this interconnection is to evacuate a large amount of power from power plants which are planned to be constructed in Kosovo until 2020,

- **Interconnection line 400 kV Nea Santa (GR) – Maritsa East 1 (BG):**

There were many versions of the new connection between Bulgaria and Greece and this is the latest planned interconnection line. It is expected, for this line, not just to increase the transfer capacity from Bulgaria to Greece, but also to increase power system security and stability with respect to the future connection of Turkey to UCTE,

- **Interkonektivni vod 400 kV Ernestinovo (HR) – Pecs (HU) (dvostruki vod):**

  Očekuje se da će novi dvostruki vod između Hrvatske i Mađarske povećati statičku sigurnost sustava. Također se očekuje povećanje uvoznih mogućnosti Hrvatske i okolnih država iz smjera CENTREL-a i Ukrajine. Ugovor za izgradnju ovog voda već su potpisale obje strane, odnosno HEP OPS i MAVIR (hrvatski i mađarski operator prijenosnog sustava), a izgradnja voda je već započela,

- **Interkonektivni vod 400 kV Zerjavinec (HR) – Cirkovce (SI) – Heviz (HU) (trokut):**

  Ova petlja ili trokut dalekovoda jedna je od opcija za završnu fazu povezivanja Slovenije, Hrvatske i Mađarske izgradnjom dvostrukog DV i njegovog uvođenja u postojeći dvostruki 400 kV DV Zerjavinec (HR) – Heviz (HU). Interkonektivni trokut bi se nalazio blizu Pince u Mađarskoj. Svrha ove petlje je međusobno povezivanje triju susjednih država. Za ovaj projekt još se očekuje konačna odluka svih triju strana,

- **Interkonektivni vod 400 kV Novi Sad (RS) – Timisoara (RO):**

  Ovaj vod trebao bi povećati stabilnost sustava, sigurnost i prijenosnu moć između sjevernih i zapadnih regija Srbije i Rumunjske. Još uvijek je potrebno izraditi studiju izvodljivosti koju pripremaju EMS (operator prijenosnog sustava Srbije) i TRANSELECTRICA (operator prijenosnog sustava Rumunjske),

- **Interkonektivni vod 400 kV Bitola (MK) – Elbasan (AL) i HVDC kabel Durres (AL) – Foggia (IT):**

  Ova dva projekta trebala bi biti potpora tzv. Koridoru 8 (EBRD projekt – povezivanje plinskog, naftnog i elektroenergetskog sustava između bugarske obale i Crnog mora te albanske obale i Jonskog mora). Obalni dio Koridora 8 bio bi finaliziran uključivanjem 400 kV DV Chervena Mogila (BG) – Stip (MK) i 400 kV DV Bitola (MK) – Elbasan (AL). Konačni rezultat bio bi otvaranje mogućnosti izvoza električne energije prema Italiji podmorskim HVDC kabelom do čvorišta Foggia. U tijeku je razrada nekoliko studija izvodljivosti i detaljnijih tehničkih studija, ali još uvijek je upitna prijenosna moć ovog kabela jer je za njegovu realizaciju potrebno pojačati prijenosnu mrežu Albanije. U ovoj je studiji prijenosna moć tog kabela postavljena na 500 MW,

- **Interkonektivni HVDC kabel Konjsko (HR) – Candia (IT):**

- **Interconnection line 400 kV Ernestinovo (HR) – Pecs (HU) (double line):**

  Double tie line between Croatia and Hungary is expected to increase the steady state security in the SEE region. The importing capability of Croatia and surrounding countries from CENTREL and Ukraine is expected to be increased as well. The contract for its construction has already been signed by both sides, HEP OPS (Croatian TSO) and MAVIR (Hugarian TSO), and line construction has already started,

- **Interconnection line 400 kV Zerjavinec (HR) – Cirkovce (SI) – Hevitz (HU) (triangle):**

  This loop or triangle of transmission lines is one of the options for final stage in connecting of Slovenia to Croatia and Hungary by building a double OHL and leading it into the existing double OHL 400 kV Zerjavinec (HR) – Hevitz (HU). Triangle connection would be formed near Pince in Hungary. The purpose of this loop of OHLs is to interconnect the three neighboring countries. The final decision about that is still expected,

- **Interconnection line 400 kV Novi Sad (RS) – Timisoara (RO):**

  This tie line should increase system stability, security and transmission capacity between the north and the west regions of Serbia and Romania. Feasibility studies are yet to be performed by the EMS (TSO of Sebia) and TRANSELECTRICA (TSO of Romania),

- **Interconnection line 400 kV Bitola (MK) – Elbasan (AL) (OHL) and HVDC Durres (AL) – Foggia (IT):**

  These two elements are supposed to be the backbone of Corridor 8 (EBRD – gas, oil and energy connection of Bulgarian coast at Black Sea and Albanian coast at Ionian Sea). The coastal part of Corridor 8 would be finalized by inclusion of OHLs 400 kV Chervena Mogila (BG) – Stip (MK) and 400 kV Bitola (MK) – Elbasan (AL). The final outcome would be the possibility to export power to Italy through submarine HVDC cable to Foggia. Several feasibility and technical studies are ongoing, but transmission capacity of this cable is still under a question mark due to many necessary reinforcements in the transmission system of Albania in case of its realization. In the present study, its transfer capacity is reduced to 500 MW,

- **Interconnection HVDC Konjsko (HR) – Candia (IT):**

Neprestan nedostatak snage u Italiji potiče na istraživanja novih načina uvoza energije putem novih interkonektivnih vodova. Jedna od tih mogućnosti je podmorski HVDC kabel iz Hrvatske prema Italiji preko Jadranskog mora. Tim vodom bi se smanjio prijenosni put električne energije od jugoistočne Europe do Italije, što je posebno važno zbog visokog opterećenja postojećih vodova u sjevernoj Italiji i susjednim državama. U ovoj je studiji prijenosna moć ovog kandidata određena na 500 MW,

— **Interkonektivni vod 400 kV Ernestinovo (HR) – Sombor (RS) – Pecs (HU) (triangle):**

Ova petlja (trokut) dalekovoda predstavljao je alternativu dvostrukom DV 400 kV Ernestinovo – Pecs. Ideja za realizaciju ovog projekta je da se dvostruki DV iz Sombora (Srbija) uvede u DV 2x400 kV Ernestinovo – Pecs. Na taj način bi se znatno povećala prijenosna moć iz Mađarske (CENTREL) prema Hrvatskoj i Srbiji. Međutim, ova konfiguracija je samo jedna od opcija jednog operatora sustava (EMS), ali nije prihvaćena od strane preostala dva operatora.

7. REZULTATI STUDIJE

Nakon provođenja analiza tokova snaga i analiza sigurnosti uslijedilo je procesiranje proračunskih rezultata kako bi se odredili kandidati za izgradnju dalekovoda koji imaju najpozitivniji utjecaj na regionalnu prijenosnu mrežu. Prema prikazanoj metodologiji primijenjen je statistički pristup koji podrazumijeva definiranje utjecaja u smislu:

— broja dodanih ili uklonjenih preopterećenja u osnovnom scenariju (opterećeni preko 100 %),
— broj dodanih ili uklonjenih kritičnih elemenata pri analizi sigurnosti ($n-1$),
— broj dodanih ili uklonjenih odstupanja napona pri analizi sigurnosti ($n-1$), i
— broj dodanih ili uklonjenih elemenata s promjenom opterećenja od 2 % MVA ili više.

Naime, potrebno je istaknuti da u ni u jednom analiziranom slučaju (sa i bez uvođenja kandidata) ni jedan element prijenosne mreže nije bio opterećen više od 100 %, tako da se uključenjem novih kandidata ne javljaju dodana ili uklonjena preopterećenja, odnosno zagušenja u mreži. Iz tog razloga primijenjen je blaži pristup kojim se bilježi popis dodanih ili uklonjenih elemenata s opterećenjem većim od 60 % dopuštenog termičkog opterećenja.

A constant deficit of power in Italy leads to the exploration of new possible ways to import energy through new tie lines. One such possible line is a submarine HVDC cable from Croatia to Italy over the Adriatic Sea. It is expected that it would reduce the transfer path of energy from the SEE to Italy, due to high loading of existing tie lines in the northern region of Italy and the neighboring countries. Transfer capacity is to be determined. In the present study, its transfer capacity is set at 500 MW,

— **Interconnection line 400 kV Ernestinovo (HR) – Sombor (RS) – Pecs (HU) (triangle):**

This loop (triangle) of OHLs was an alternative to the double OHL 400 kV Ernestinovo – Pecs. The double OHL would be conducted from Sombor (Serbia) into one of two lines Ernestinovo – Pecs. In this way, transfer capacities from Hungary (CENTREL) to Croatia and Serbia would be significantly increased. This configuration has only been considered as an option by one corresponding TSO (Serbian EMS), but has not accepted by the other TSOs.

7 STUDY RESULTS

The process of load flow and contingency analyses is followed by the processing of the calculated results in order to determine which transmission line candidate has the most positive influence on the regional transmission grid of the GIS countries. According to the given methodology, the statistical approach was applied to examine all results from load flow and contingency analyses. Statistical approach is based on counting influences in terms of:

— number of added or removed overloads in base case (loaded over 100 %),
— number of added or removed contingency critical elements,
— number of added or removed contingency voltage violations, and
— number of relieved or loaded elements by more than 2 % of MVA rate (additional set of data).

It must be pointed out that in none of the cases (with and without candidates) are there loadings of transmission elements higher than 100 %, so there are no added or removed bottlenecks to be numbered. This is the reason why a more relaxed approach was applied by observing the list of critically loaded elements which are actually loaded more than 60 %.

A number of influences appeared in each load flow case (12 cases in total), these being assembled in Table 9. In order to prioritize transmission line can-

U tom slučaju u svim analiziranim scenarijima (ukupno 12) pojavljuje se niz utjecaja navedenih u tablici 9.

didates, it is necessary to simplify the sorting out of 8 sets of data.

Tablica 9 – Ukupni broj pozitivnih i negativnih utjecaja kandidata za izgradnju dalekovoda
Table 9 – Total numbers of positive and negative influences of transmission candidates

Broj / No.	Kandidati / Candidates	Tokovi snaga / Load Flow (n)				$(n-1)$ analiza sigurnosti / Contigency analysis			
		Ukupno (unutra/van) / Total (in/out)		Ukupno / Total (delta > 2 %)		Ukupno preopterećenje / Total overload $(n-1)$		Ukupno naponi / Total voltages $(n-1)$	
		Uklonjeni / Removed	Dodani / Added	Rasterećeni / Relieved	Opterećeni / Loaded	Uklonjeni / Removed	Dodani / Added	Uklonjeni / Removed	Dodani / Added
1	Kashar – Kosovo B	2	1	4	1	5	0	28	0
2	Maritsa Istok – Nea Santa	0	0	0	0	1	0	4	0
3	Ernestinovo – Pecs	3	1	16	0	9	2	1	0
4	Žerjavinec – Cirkovce – Heviz	1	0	10	0	3	0	0	0
5	Novi Sad – Temisoara	0	0	3	0	1	0	1	0
6	Bitola – Elbasan & Durres – Foggia	7	15	27	29	3	7	1	29
7	Konjsko – Candia	7	22	11	36	4	6	3	22
8	Ernestinovo – Sombor – Pecs	3	1	15	0	8	228	1	1

Najjednostavniji način za kvantifikaciju utjecaja kandidata u nekom scenariju je da se broj dodanih kritičnih stanja oduzme od broja uklopnjenih kritičnih stanja. Taj razlika bi se mogla smatrati koeficijentom koristi (eng. *benefit coefficient*). Ako je koeficijent viši, to znači da taj kandidat svojim radom doprinosi elektroenergetskom sustavu (s više uklonjenih preopterećenja ili slučajeva nezadovoljavajućih naponskih prilika). U slučaju kada je navedeni koeficijent manji od nule, to znači da taj kandidat donosi više negativnih, nego pozitivnih učinaka u elektroenergetskom sustavu.

Prioritizacija kandidata za izgradnju dalekovoda provedena je određivanjem koeficijenata koristi za svakog kandidata. Prema ranije navedenoj metodologiji i kriterijima, uklanjanje zagušenja iz osnovnog slučaja (raspoloživo n elemenata sustava) ima najveći utjecaj na prioritizaciju. Drugi kriterij za prioritizaciju kandidata odnosi se otklanjanje preopterećenja i nezadovoljavajućih naponski prilika pri raspoloživosti $n-1$ elementa sustava.

Na posljednjem mjestu, kao najmanje važan kriterij, nalazi se promjena tokova snaga veća od $2\ \%$. Ovaj kriterij nije dio standardne metodologije, već je za ovu priliku pridodan navedenoj standardnoj metodologiji kako bi se dobio točniji uvid. Rezultati primijenjenih kriterija navedeni su u tablici 10. Budući da nema dodanih niti uklonjenih preopterećenih elemenata jasno je da se u prvom stupcu nalaze same nule radi primjene standardne metodologije za prioritizaciju. S obzirom na to da su prema prvom kriteriju svi kandidati jednako važni, svrstavanje je izvršeno primjenom preostala tri kriterija navedenim u drugom, trećem i četvrtom stupcu.

The easiest way to quantify the effectiveness of presence of transmission line candidate in some base case is to subtract the number of obstructions from the number of contributions and the result could be proclaimed to be a benefit coefficient. If this coefficient is higher, it means that some particular transmission line (with this coefficient) is bringing benefit to the power system with its operation (with more removed overloading or voltage violations). In case when the coefficient is less than zero, this particular candidate brings more unwanted effects to a certain power system.

Prioritization of transmission line candidates is conducted by sorting out the benefit coefficients corresponding to each transmission line. According to the methodology of transmission investment criteria, removal of bottlenecks from the base case has the most important influence on prioritization. Then, contingency events have come as the second criterion for sorting out (overloading and voltage violations). In the last place, as the least important criterion, there is the change of current flow at a rate of more than $2\ \%\ \mathrm{MVA}$. This criterion is added to the standard methodology in order to make the sorting out more correct. If these criterions are applied in this order to the calculated benefit coefficients, the priority list of candidates is obtained and given in Table 10. It is obvious that there are all zeros in the first column because of application of the strict prioritization methodology. Since by the first criterion all candidates were of the same importance, the sorting out was completed through the next three criterions.

Tablica 10 – Popis kandidata za izgradnju dalekovoda nakon rangiranja prema originalnoj metodologiji Transmission Network Investment Criteria
Table 10 – List of transmission candidates after ranking according to the original Transmission Network Investment Criteria methodology

	Kandidati / Candidates	U/van / In/out	Preopterećenje / over $(n-1)$	Napon / Voltage $(n-1)$	Delta / Delta $>2\,\%$
1	Ernestinovo – Pecs	0	7	1	16
2	Ernestinovo – Sombor – Pecs	0	6	0	15
3	Kashar – Kosovo B	0	5	28	3
4	Žerjavinec – Cirkovce – Heviz	0	3	0	10
5	Maritsa Istok – Nea Santa	0	1	4	0
6	Novi Sad – Timisoara	0	1	1	3
7	Konjsko – Candia	0	–2	–19	–25
8	Bitola –Elbasan&Durres – Foggia	0	–4	–28	–2

Radi provjere rezultata prioritizacije korišten je blaži pristup tako što se pobrojila količina dodanih ili uklonjenih elemenata opterećenih više od 60 %. Primjenom ovog kriterija umjesto ranije navedenog prvog, i to prije kriterija analize sigurnosti, prioritizacijom se dobiva popis kandidata prikazan u tablici 11. Iz tablice 11 vidljivo je da se popis kandidata razlikuje samo u dva posljednja mjesta koja su međusobno zamijenila mjesta (HVDC kabeli), ali s obzirom da oba kandidata imaju negativne koeficijente koristi, ta razlika ne utječe na poziciju kandidata.

For the purpose of checking the result of prioritization, a more relaxed approach was used by counting the number of addition or removal of elements which are loaded by more than 60 % With the usage of this criterion as the first one in front of the contingency analysis criterions, the prioritization produces the candidate list given in Table 11. Table 11 reveals that the list of candidates differs only in the last two places which are replaced (HVDC cables), but since both of these candidates have negative benefit coefficients, this difference does not affect the position of candidates in the first three places.

Tablica 11 – Popis kandidata za izgradnju dalekovoda nakon rangiranja prema izmijenjenoj (blažoj) metodologiji Transmission Network Investment Criteria
Table 11 – List of transmission candidates after ranking according to the modified (relaxed) Transmission Network Investment Criteria methodology

	Kandidati / Candidates	U/van / In/out	preopterećenje / Over $(n-1)$	Napon / Voltage $(n-1)$	Delta / Delta $>2\,\%$
1	Ernestinovo – Pecs	2	7	1	16
2	Ernestinovo – Sombor-Pecs	2	6	0	15
3	Kashar – Kosovo B	1	5	28	3
4	Žerjavinec – Cirkovce – Heviz	1	3	0	10
5	Maritsa Istok – Nea Santa	0	1	4	0
6	Novi Sad – Timisoara	0	1	1	3
7	Bitola –Elbasan & Durres – Foggia	–8	–4	–28	–2
8	Konjsko – Candia	–15	–2	–19	–25

Određeni kandidati pružaju iznimnu korist u pogledu naponskih prilika, na primjer DV 400 kV Kashar – Kosovo B, dok neki drugi kandidati imaju iznimno loš utjecaj na napon koji je iskazan u obliku velikog negativnog koeficijenta. Već je iz koeficijenata koristi moguće zaključiti ima li neki element negativan ili pozitivan učinak na regionalnu prijenosnu mrežu, međutim, kako bi se zaista odredilo na koji način kandidat utječe na elektroenergetski sustav, potrebno je pozorno analizirati svaki scenarij tokova snaga i rezultate analiza sigurnosti.

Nakon završetka svih analiza tokova snaga i analiza sigurnosti te primjene zadane metodologije za prioritizaciju, dobiva se popis prioriteta za nove dalekovode u regiji i to prema sljedećem redoslijedu (slika 9):

1. DV 400 kV Ernestinovo (HR) – Pecs (HU) (dvostruki vod),

Some transmission candidates are extremely beneficial for contingency voltages, for instance, the OHL 400 kV Kashar – Kosovo B. Some other candidates have extremely bad influence which is represented by the high negative coefficient. Just by looking at the benefit coefficients, it could be concluded if an element has good or bad influence on power transfer at the regional level, but in order to really identify how a transmission line candidate affects electrical quantities in the power system, each load flow and contingency result must be analyzed thoroughly.

After performing all load flow and contingency analyses, and after using the given prioritization methodology, the list of priorities for new transmission lines in the GIS region emerges in this order (Figure 9):

1. OHL 400 kVErnestinovo (HR) – Pecs (HU) (double line),

2. DV 400 kV Ernestinovo (HR) – Sombor (RS) – Pecs (HU) (trokut),
3. DV 400 kV Kashar (AL) – Kosovo B (KS),
4. DV 400 kV Zerjavinec (HR) – Cirkovce (SI) – Heviz (HU) (trokut),
5. DV 400 kV Marica Istok I (BG) – Nea Santa (GR),
6. DV 400 kV Novi Sad (RS) – Timisoara (RO),
7. HVDC 400 kV Konjsko (HR) – Candia (IT),
8. HVDC 400 kV Durres (AL) – Foggia (IT) + DV 400 kV Bitola (MK) – Elbasan (AL).

2. OHL 400 kV Ernestinovo (HR) – Sombor (RS) – Pecs (HU) (triangle),
3. OHL 400 kV Kashar (AL) – Kosovo B (KS),
4. OHL 400 kV Zerjavinec (HR) – Cirkovce (SI) – Hevitz (HU) (triangle),
5. OHL 400 kV Marica Istok I (BG) – Nea Santa (GR),
6. OHL 400 kV Novi Sad (RS) – Timisoara (RO),
7. HVDC 400 kV Konjsko (HR) – Candia (IT),
8. HVDC V Durres (AL) – Foggia (IT) + OHL 400 kV Bitola (MK) – Elbasan (AL).

Slika 9 — Rangirani kandidati za izgradnju u regiji GIS-a

Figure 9 — Ranked transmission line candidates in the GIS region

Dvostruki DV Ernestinovo – Pecs ostvaruje najbolji učinak u prijenosnoj mreži jugoistočne Europe, dok HVDC 400 kV Durres – Foggia + DV 400 kV Bitola – Elbasan imaju najniže korisne učinke. Iz slika 10 i 11 vidljivo je da postoji vrlo mala, ali primjetna razlika u koristi dvostrukog DV 400 kV Ernestinovo – Pecs i DV 400 kV trokuta Ernestinovo – Sombor – Pecs. Osim toga, jasno je i da se ova dva projekta međusobno isključuju.

Double OHL Ernestinovo – Pecs yields the best effects in the SEE transmission grid, while HVDC 400 kV Durres – Foggia + OHL 400 kV Bitola – Elbasan has the lowest beneficial effects. From the Tables 10 and 11 it is obvious that there is very small, but distinctive difference in benefits of double OHL 400 kV Ernestinovo – Pecs and OHL 400 kV triangle Ernestinovo – Sombor – Pecs. Also, it is clear that these two projects are not complement, but competent.

8 ZAKLJUČCI

Sveukupni zaključci ove analize mogu se iskazati na slijedeći način:

- Prema kriterijima definiranim u studiji *Transmission Network Investment Criteria* nijedan od proučavanih kandidata ne donosi značajna poboljšanja u mogućnostima razmjene unutar regije. Drugim riječima, prijenosna mreža jugoistočne Europe u 2015. godini moći će podržati planiranu razinu izgradnje novih elektrana čak i bez izgradnje ijednog kandidata - interkonektivnog voda,
- Mogućnosti razmjene u regiji ograničene su

8 CONCLUSIONS

Overall conclusions of the analysis can be stated as follows:

- According to Transmission Network Investment Criteria, none of the observed interconnection candidate lines bring significant improvement to the exchange possibilities in the region. In other words, the SEE transmission grid in 2015 can support planned injection of power from new power plants even without any interconnection transmission line candidate,
- Exchange possibilities in the region are limited by the bottlenecks in internal networks, mainly in Albania, Romania and Bulgaria. Some of

zagušenjima unutar pojedinih sustava, većinom u Albaniji, Rumunjskoj i Bugarskoj. Neka od tih zagušenja moguće je ukloniti primjenom pogonskih i dispečerskih mjera,
— Kao krajnji rezultat, usporedba utjecaja kandidata rezultirala je ljestvicom prioriteta - najviši prioritet ima 2x400 kV DV Ernestinovo (HR) - Pecs (HU), koji je već u izgradnji. Slijedeći vod na listi prioriteta je 400 kV DV Kashar (AL) – Kosovo B (KS).

Pri provođenju analize najprije je određeno osam kandidata za izgradnju i zatim je sortiran njihov utjecaj na tokove snage u državama GIS-a za scenarij s maksimalnim zimskim, maksimalnim ljetnim i minimalnim ljetnim opterećenjem 2015. godine. Analizom tokova snaga i sigurnosti uspoređeni su utjecaji svih kandidata na strujne i naponske prilike u regiji. Prema metodologiji definiranoj u [3] ti utjecaji statistički su analizirani na temelju čega je definirana lista prioriteta za poboljšanje postojeće regionalne prijenosne mreže.

Krajnji rezultat prioritizacije je slijedeća lista regionalnih prioriteta:

1. DV 400 kV Ernestinovo (HR) – Pecs (HU) (dvostruki vod),
2. DV 400 kV Ernestinovo (HR) – Sombor (RS) – Pecs (HU) (trokut),
3. DV 400 kV Kashar (AL) – Kosovo B (KS),
4. DV 400 kV Zerjavinec (HR) – Cirkovce (SI) – Heviz (HU) (trokut),
5. DV 400 kV Marica Istok I (BG) – Nea Santa (GR),
6. DV 400 kV Novi Sad (RS) – Timisoara (RO),
7. HVDC 400 kV Konjsko (HR) – Candia (IT),
8. HVDC 400 kV Durres (AL) – Foggia (IT) + DV 400 kV Bitola (MK) – Elbasan (AL).

Konačno, prije iznošenja komentara za svaki od navedenih kandidata za izgradnju i njihovih pozicija na ljestvici prioriteta, potrebno je spomenuti nekoliko važnih činjenica. Vezano uz bilancu, kontrolna područja UCTE-a i IPS/UPS imaju višak snage, dok su elektroenergetski sustavi Italije, Grčke i Turske jako deficitarni. Uvozi Grčke i Turske definirani su na razini od 2 000 MW (1 200 MW je uvoz Turske, 400 MW uvoz Grčke, a 400 MW je prijenos snage preko HVDC kabela Arachtos (GR) – Galatina (IT) u Italiju). Ovaj veliki uvoz snage usmjerio je tokove snaga iz država obuhvaćenih GIS-om prema krajnjem jugu jugoistočne Europe u svim slučajevima (čak i u scenarijima kada države GIS-a izvoze u zapadni dio UCTE-a). Također, pojavljuju se i veliki tokovi snaga iz IPS/UPS-a (Ukrajina) i CENTREL-a (Slovačka) u svim analiziranim pogonskim režimima zbog velikog uvoza Mađarske (–1 200 MW) i Italije (–9 250 MW).

these bottlenecks can be removed by applying operational and dispatching control remedial measures,
— As the final outcome, comparison of impacts of candidate interconnection lines resulted with a priority list - the highest priority was allocated to the OHL 2x400 kV Ernestinovo (HR),
— Pecs (HU) that is already under construction. Besides that, the most promising line is the OHL 400 kV Kashar (AL) – Kosovo B (KS).

Having this in mind, eight transmission line candidates were identified first and then their impacts to load flows in the GIS countries were sorted for the scenario with the maximum load in the winter 2015. Load flow and contingency analyses produced results which were used to compare the impact of each candidate through a number of benefits or violations in the regional power system. According to the methodology defined in the Transmission Network Investment Criteria these benefits were analyzed statistically and sorted in order to select the transmission line with the highest priority for upgrading the existing regional transmission grid.

Final outcome of the prioritization was the following list of ranked transmission lines:

1.
2. OHL 400 kV Ernestinovo (HR) – Pecs (HU) (double line),
3. OHL 400 kV Ernestinovo (HR) – Sombor (RS) – Pecs (HU) (triangle),
4. OHL 400 kV Kashar (AL) – Kosovo B (KS),
5. OHL 400 kV Zerjavinec (HR) – Cirkovce (SI) – Hevitz (HU) (triangle),
6. OHL 400 kV Marica Istok I (BG) – Nea Santa (GR),
7. OHL 400 kV Novi Sad (RS) – Timisoara (RO),
8. HVDC 400 kV Konjsko (HR) – Candia (IT),
9. HVDC 400 kV Durres (AL) – Foggia (IT) + OHL 400 kV Bitola (MK) – Elbasan (AL).

In order to provide comments for each of these transmission line candidates and their positions in the list of priorities, some important facts must be mentioned. In relation to load flow power balance for the GIS countries in 2015, control areas of UCTE and IPS/UPS have an excess of power while power systems of Italy, Greece and Turkey were defined as importing regions with high amounts of imported power. Imports of Greece and Turkey were fixed to 2 000 MW (1 200 MW) is import of Turkey, 400 MW is import of Greece and 400 MW is transit of power over HVDC Arachtos (GR) – Galatina (IT) to Italy). This high power import routed all power flow from GIS countries toward south of SEE in all the cases (even when GIS countries exported power to western UCTE). A high amount of power flows from the IPS/UPS (Ukraine) and CENTREL (Slovakia) in all operating regimes due to the high import of Hungary (–1 200 MW) and Italy (–9 250 MW).

Općenito gledano, iako postoje tri definirana smjera razmjena (od IPS/UPS-a prema državama GIS-a, od država GIS-a prema zapadnom dijelu UCTE-a i od država GIS-a prema Italiji), tokovi snaga ne prate u cjelosti glavne smjerove razmjena zbog raznolikosti pojedinačnih uvoza i izvoza država GIS-a, kao i zbog zemalja uvoznica na sjeveru i jugu regije.

DV 2x400 kV **Ernestinovo (HR) – Pecs (HU)** rangiran je kao prvi na ljestvici prioriteta u regiji. Od svih kandidata ovaj vod daje najveći doprinos regionalnim tokovima snaga u režimima suhe hidrologije, kada regija GIS-a uvozi električnu energiju iz IPS/UPS-a, te u režimima kada je regija GIS-a uravnotežena. Veliki iznosi snage u svim scenarijima teku od Mađarske prema Turskoj i Grčkoj, preko Rumunjske, Srbije i Bugarske – dio tog toka je preusmjeren prema zapadnom dijelu regije GIS-a. U slučaju izgradnje dvostrukog DV Ernestinovo – Pecs, tok snage je preusmjeren – umjesto iz Mađarske preko Rumunjske i Srbije, snaga izravno teče iz Mađarske u Hrvatsku.

DV 400 kV **Ernestinovo (HR) – Sombor (RS) – Pecs (HU)** (trokut) je alternativa ili drugi na ljestvici prioriteta. Zapravo, ovaj kandidat za izgradnju dalekovoda je izmijenjena verzija kandidata koji se nalazi na prvom mjestu, jer se jedan vod uvodi/izvodi u TS 400 kV Sombor u Srbiji. Učinci pogona ovog trokuta su nešto lošiji od učinaka navedenog dvosistemskog voda Ernestinovo (HR) – Pecs (HU).

DV 400 kV **Kashar (AL) – Kosovo B (KS)** je treći na ljestvici prioriteta (ustvari drugi, s obzirom na to da su prva dva projekta s liste prioriteta kompetitivni). Razlog zbog kojeg je ovaj DV kandidat na trećem mjestu je njegov iznimno koristan učinak na albanski sustav u svim režimima pogona i razmjena. Konceptualno gledano, mreža 400 kV u Albaniji sastoji se od jedne poveznice između Crne Gore i Grčke bez ijedne proizvodne jedinice povezane na ovu naponsku razinu. U slučaju bilo kojeg većeg prijenosa snage, ovaj bi kandidat omogućio potrebnu podršku u pogledu održanja statičke sigurnosti u ovom dijelu sustava. Smatra se da se ovaj kandidat ne bi trebao tretirati kao odvojeni kandidat, nego zajedno s jednim HVDC kabelom iz Albanije prema Italiji. Još jedan razlog u korist ovog zaključka je vezan uz priključak novih proizvodnih jedinica na Kosovu (Kosovo B i C) do 2015. godine.

DV 400 kV **Zerjavinec (HR) – Cirkovce (SI) – Heviz (HU)** (trokut) je četvrti kandidat na ljestvici prioriteta i nalazi se na krajnjem sjeverozapadu razmatrane regije. Ovaj kandidat je ustvari nadgradnja postojećeg 400 kV dvostrukog interkonektivnog voda Zerjavinec (HR) – Heviz (H) (jedan od vodova se uvodi/izvodi u TS 400 kV Cirkovce u Sloveniji). Koristi od ovog trokuta nisu u potpuno-

Generally, although there are three defined directions of power flow (from IPS/UPS to GIS countries, from GIS countries to western UCTE and from GIS countries to Italy), power flow does not follow the defined direction of exchange in any of these cases because of the mixture of exporting and importing GIS countries, as well as because of importing countries to the north and south of the GIS ones.

OHL 2x400 kV **Ernestinovo (HR) – Pecs (HU)** is ranked as the first one on the list of priorities. Among all the candidates, this line brings the highest contribution to the regional power flows in regimes of low water inflow when the GIS region imports power from the IPS/UPS and in regimes when the GIS region is balanced. Large amounts of power always flow from Hungary toward Turkey and Greece, over Romania, Serbia and Bulgaria - part of this flow is diverted to the western part of the GIS region. In case of presence of a double OHL Ernestinovo – Pecs, the path of power is shortened - instead of flowing from Hungary over Romania and Serbia, power directly flows from Hungary to Croatia.

OHL 400 kV **Ernestinovo (HR) – Sombor (RS) – Pecs (HU)** (triangle) is the alternative or the second one on the list of priorities. In fact, this transmission line candidate is a modification of the first ranked candidate since one of the transmission lines is fed into the S/S 400 kV Sombor in Serbia. The effects of operation of this triangle are slightly worse than the effects of the above mentioned double circuit line Ernestinovo (HR) – Pecs (HU).

OHL 400 kV **Kashar (AL) – Kosovo B (KS)** is the third one (in fact the second, since the first two priority projects are competent) on the list of priorities. The reason for having this OHL candidate in the third place is found in its extremely beneficial effect on neighboring Albania in all the regimes of operation or exchange. Conceptually, 400 kV the grid of Albania consists of a single backbone connection from Montenegro to Greece without any generation connected to this voltage level. In case of any heavy power transfer, this candidate provides the needed voltage support maintaining the steady state security in this part of the GIS region. It is considered that this candidate should not be treated as a separate transmission line candidate, but with an HVDC candidate which might lead from Albania. Another supporting reason for this conclusion is related to the connection of new power generation in UNMIK (Kosovo B and C) until 2015.

OHL 400 kV **Zerjavinec (HR) – Cirkovce (SI) – Heviz (HU)** (triangle) is the fourth candidate in the list of priorities. Situated in the far north-west of the GIS region, this transmission line candidate is actually an upgrade of the existing double interconnection line 400 kV Zerjavinec (HR) – Heviz (H) (one of lines is fed into S/S 400 kV Cirkovce in Slovenia). The benefits of this OHL loop are not fully expressed in the sti izražene u razmatranim scenarijima u okviru ove studije prvenstveno zbog svog položaja, odnosno smjera razmjena. Ovaj trokut, u kombinaciji s DV 2x400 kV Okroglo (SI) – Udine (IT), mogao bi još više pridonijeti prijenosu snage od IPS/UPS-a direktno prema UCTE-u, odnosno Italiji.

DV 400 kV **Marica Istok I (BG) – Nea Santa (GR)** je peti kandidat na ljestvici prioriteta. Za razliku od prethodnog kandidata, ovaj dalekovod se nalaz na krajnjem jugoistoku regije. U usporedbi s ostalim kandidatima, ovaj vod ne donosi velike promjene u situacijama vezanim uz središnji dio regije zbog njegovog položaja i već definiranog smjera tokova snage iz Bugarske prema Turskoj. S obzirom na to da postojeća dva voda (prema čvorištima Babaeski i Hamitabat u Turskoj) nisu visoko opterećena, pogon ovog kandidata od čvorišta Marica Istok I do čvorišta Nea Santa samo bi redistribuirao tokove snaga preusmjeravajući jedan dio snage preko Grčke. Veći doprinos ovog kandidata mogao bi se ogledati u scenarijima s puno većim uvozom Turske i Grčke ili u scenarijima izvoza iz Turske u UCTE.

DV 400 kV **Novi Sad (RS) – Timisoara (RO)** je šesti kandidat na ljestvici prioriteta. Doprinos ovog kandidata je neutralan u odnosu na ostale kandidate s obzirom na to da ovaj kandidat ne dodaje, niti uklanja problematična stanja sustava. To je posljedica prethodno definiranih tokova snaga od sjevera do juga regije preko Srbije i Rumunjske istodobno, stoga u slučaju izgradnje ovog dalekovoda ne dolazi do znatnih promjena u tokovima snaga.

HVDC 400 kV **Konjsko (HR) – Candia (IT)** je sedmi kandidat na ljestvici prioriteta. Glavna svrha ovog kandidata je prijenos 500 MW snage prema Italiji (kasnije su bile izvršene analize prijenosne moći od 1 000 MW, ali se pokazalo da to ne utječe značajnije na rezultate). Iako navedena razina snage nije kritična (prirodna snaga 400 kV dalekovoda), pogon ovog podmorskog kabela donosi više problema prijenosnoj mreži zbog nedovoljno jakog priključnog čvorišta u Konjskom. Osnovni zaključak za ovaj projekt je da je priključkom u čvorište Konjsko nužno pojačati okolnu prijenosnu mrežu u regiji.

Kombinacija HVDC 400 kV **Durres (AL) – Foggia (IT) i DV 400 kV Bitola (MK) – Elbasan (AL)** je osmi kandidat na ljestvici prioriteta. Ova dva elementa čine ključni dio tzv. Koridora 8 od Crnog mora do Jonskog mora. Još jednom, kao u slučaju prethodnog kandidata, prijenos snage 500 MW prema Italiji uzrokuje preopterećenja i preniske napone u Albaniji zbog nerazvijene 400 kV mreže u ovom dijelu regije. Unatoč tome, ove je probleme moguće učinkovito riješiti uključivanjem 400 kV DV Kashar – Kosovo B koji bi mogao pružiti potporu na 400 kV naponskoj razini za evakuaciju snage iz TE na Kosovu.

defined scenarios of the present study due to the position and direction of exchanges. This triangle, combined with the double OHL 400 kV Okroglo (SI) – Udine (IT), might contribute more to power transfers from IPS/UPS directly to UCTE and Italy.

OHL 400 kV **Marica Istok I (BG) – Nea Santa (GR)** is the fifth candidate in the list of priorities. As opposed to the previous candidate, this line is situated in the far south-east of GIS region. In comparison with the other candidates, this line does not bring many differences in the situations related to the middle of the GIS region due to its position and already defined power flow direction from Bulgaria to Turkey. Since the existing two lines (to Babaeski and Hamitabat in Turkey) already have enough reserve transmission capacity, operation of the new candidate from Marica Istok I to Nea Santa only redistributes the power flow by diverting one part over Greece. Much higher contribution of this candidate could be noticed in the scenarios with much higher power import of Turkey and Greece or export of Turkey to UCTE.

OHL 400 kV **Novi Sad (RS) – Timisoara (RO)** is the sixth candidate on the list of priorities. The contribution of this candidate is neutral in comparison to the other candidates since there is not much gain and loss with its operation. This is a consequence of the predefined power flows from north to south of the GIS region over Serbia and Romania simultaneously, so there are no significant changes in the line flows in the presence of this line.

HVDC 400 kV **Konjsko (HR) – Candia (IT)** is the seventh candidate on the list of priorities. The main purpose of this candidate is 500 MW power transfer toward Italy (later on, there were analyses with 1 000 MW of HVDC capacity not bringing more benefit). Although the amount of power is not critical (natural power of 400 kV transmission line), operation of this submarine cable brings more problems to the GIS transmission grid due to the weak connection point in Konjsko. The main conclusion about this cable is that the connection at Konjsko must be reinforced.

Combination of HVDC 400 kV **Durres (AL) – Foggia (IT) and OHL** 400 kV **Bitola (MK) – Elbasan (AL)** is the eighth candidate on the list of priorities. These two elements represent an essential part of the Corridor 8 energy connection from the Black Sea to the Ionian Sea. Once again, just as with the previous candidate, 500 MW power transfer towards Italy causes overloads and low voltages in Albania due to the undeveloped 400 kV grid in this part of the GIS region. However, these problems could be solved effectively with the inclusion of the OHL 400 kV Kashar – Kosovo B which may bring higher voltage support to the 400 kV grid and power transfer from TPP situated in the UNMIK.

Kao što je prethodno rečeno, sveukupni zaključak ove studije je sljedeći: prijenosna mreža regije jugoistočne Europe, a posebice regije obuhvaćene studijom GIS-a, u stanju je podržati predviđeni razvoj proizvodne djelatnosti do 2015. (metode alokacije NTC-a i njegova primjena nije analizirana u sklopu ove studije). Postojeća prijenosna mreža s već ostalim pretpostavljenim interkonektivnim vodovima koji će se sigurno realizirati omogućuje siguran prijenos snage bez ikakvih preopterećenja ili nezadovoljavajućih naponskih prilika. Prisutnost novih kandidata ne donosi značajnije promjene u tokovima snaga s planerskog aspekta, ali pridonosi mogućim novim scenarijima razmjena snaga unutar regije i prema okolnim regijama.

As stated before, the overall conclusion of the present study is the following: the transmission grid of the SEE region, and the GIS one in particular, can sustain envisioned generation development and power injection until 2015 (NTC allocation methods and its application were not analyzed within this planning purpose study). The existing transmission grid with the already presumed interconnection lines enables secure power transfer without any overloaded branches or voltage magnitudes lower than the limit defined by the Grid Codes of the participating TSOs. The presence of the new transmission line candidates does not bring too many changes in power flow composition from the planning viewpoint, but contributes somewhat to certain exchange scenarios.

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EKSPERIMENTALNI FEROREZONANTNI KRUG KAO FIZIČKI MODEL FEROREZONANTNOG DIJELA ELEKTROENERGETSKE MREŽE

EXPERIMENTAL FERRORESONANT CIRCUIT AS A PHYSICAL MODEL OF A FERRORESONANT PART OF THE ELECTRICAL POWER NETWORK

Kruno Miličević – Denis Pelin, Osijek, Hrvatska

Članak prikazuje vrste ferorezonancije kao i dio elektroenergetske mreže u kojemu je ferorezonancija moguća. Eksperimentalno istraživanje ferorezonantnih dijelova elektroenergetske mreže nije praktički moguće. Stoga je u laboratoriju realiziran eksperimentalni ferorezonantni krug kao fizički model ferorezonantnog dijela elektroenergetske mreže na temelju vrijednosti parametara 230 kV-ne transformatorske stanice Dorsey (Manitoba, Kanada). Normirani parametri eksperimentalnog ferorezonantnog kruga i 230 kV-ne transformatorske stanice Dorsey uspoređeni su kao i dobiveni rezultati mjerenja.

The paper presents types of ferroresonance as well as a part of the electrical power network in which the ferroresonance could occur. The experimental investigation of the ferroresonant parts of the electrical power network is not practically possible. Therefore, an experimental ferroresonant circuit is realized in the laboratory as a physical model of a ferroresonant part of the electrical power network, based on the 230-kV Converter Station Dorsey (Manitoba, Canada). Per-unit parameter values of the experimental ferroresonant circuit and 230-kV Converter Station Dorsey are compared as well as the results obtained from the measurements.

Ključne riječi: elektroenergetska mreža; ferorezonancija; ferorezonantni krug; fizički model; vrste ustaljenih stanja
Keywords: electrical power network; ferroresonance; ferroresonant circuit; physical model; steady-state types

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1 UVOD

Ferorezonancija je složena nelinearna električna pojava koja može uzrokovati napone transformatora nekoliko puta veće od nazivnih vrijednosti. Dijelovi elektroenergetske mreže u kojima je ferorezonancija moguća ovdje će se zvati ferorezonantni dijelovi elektroenergetske mreže.

Ferorezonantni dijelovi elektroenergetske mreže sastoje se od nelinearne zavojnice sa željeznom jezgrom koja je napajana preko komponente ili dijela elektroenergetske mreže, kapacitivnost kojih nije zanemariva. Pritom nelinearna zavojnica može biti jednofazni transformator u praznom hodu ili faza trofaznog transformatora u praznom hodu.

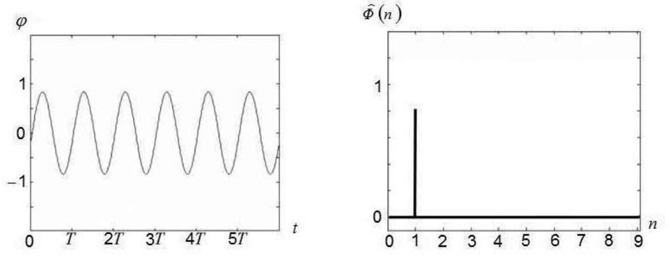
Promjena vrste ustaljenog stanja uzrokovana malom promjenom vrijednosti parametara naziva se bifurkacija. U ferorezonantnom krugu, sve bifurkacije koje uzrokuju promjenu jednoharmonijskog (slika 1) u bilo koje višeharmonijsko ustaljeno stanje sa značajno većim vrijednostima varijabli stanja naziva se ferorezonancija.

1 INTRODUCTION

Ferroresonance is a complicated nonlinear electrical phenomenon which can lead to transformer voltages several times the normal equipment ratings. Parts of electrical power network in which ferroresonance can occur are called here the ferroresonant parts of the electrical power network.

Ferroresonant parts of the electrical power network comprise a nonlinear coil with an iron core that is fed through a component or a part of the electrical power network, the capacitance of which is not negligible. Thereby, the nonlinear coil can be an unloaded single phase transformer, or a phase of an unloaded three-phase transformer.

Sudden change of steady-state types caused by a small change made to the parameter values is called a bifurcation. In a ferroresonant circuit, bifurcations that cause a change from monoharmonic (Figure 1) to any polyharmonic steady state with significantly higher state-variable values are usually named a ferroresonance.



a) valni oblik toka zavojnice / waveform of coil flux

b) harmonijski spektar toka zavojnice / harmonic spectrum of coil flux

Slika 1 — Primjer jednoharmonijskog ustaljenog stanja
Figure 1 — Example of monoharmonic steady state

Identificirane su tri osnovne vrste ferorezonancije [1] i [2]: ferorezonancija osnovne frekvencije, podharmonijska ferorezonancija i kaotična ferorezonancija. Svaka od vrsta ferorezonancije rezultira višeharmonijskim ustaljenim stanjem s različitim harmonijskim spektrom odabrane varijable stanja, npr. toka zavojnice φ gdje je $\hat{\Phi}(n)$ vršna vrijednost n-tog harmonika:

- ferorezonancija osnovne frekvencije rezultira ustaljenim stanjem koje sadrži više harmonike, frekvencije kojih su neparni višekratnici frekvencije izvora ω (slika 2):

Three basic types of ferroresonance have been identified [1] and [2]: the fundamental frequency ferroresonance, subharmonic ferroresonance and chaotic ferroresonance. Each type of ferroresonance results in a higher harmonic steady state with a different harmonic spectrum of a chosen state variable, e.g. of coil flux φ with the peak value $\hat{\Phi}(n)$ of the n-th harmonic:

- fundamental frequency ferroresonance results in a steady state which contains higher harmonics, frequencies of which are odd multiples of source frequency ω (Figure 2):

$$\varphi = \sum_{n} \hat{\Phi}(n) \cdot \sin(n\omega t + \alpha_n), \quad n = 1,\ 3,\ 5,\ 7,\ \ldots, \qquad (1)$$

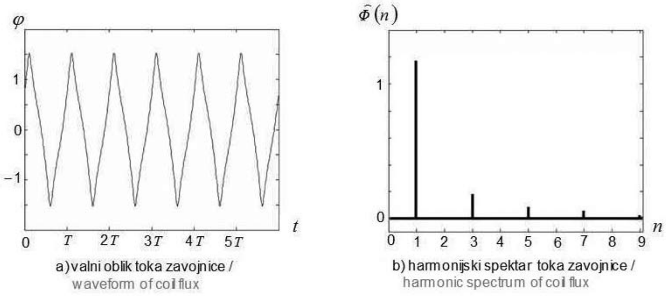
ili ustaljenim stanjem koje sadrži sve cjelobrojne više harmonike (slika 3):

or in a steady state which contains all integer higher harmonics (Figure 3):

$$\varphi = \sum_n \hat{\Phi}(n) \cdot \sin(n\omega t + \alpha_n), \quad n = 0,\ 1,\ 2,\ 3,\ 4, \ldots \qquad (2)$$

Promjena jednoharmonijskog ustaljenog stanja u ustaljeno stanje s neparnim višim harmonicima (1) naziva se ferorezonantni skok. Pojava ustaljenog stanja (2) naziva se lom simetrije ili viljuškasta bifurkacija [3] i [4].

The change from monoharmonic steady state into a steady state with odd higher harmonics (1) is called the ferroresonant jump. Occurrence of a steady state (2) is called the symmetry-breaking or the pitchfork bifurcation [3] and [4].

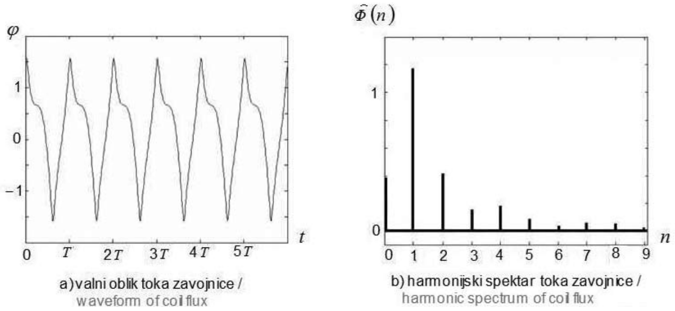


a) valni oblik toka zavojnice / waveform of coil flux

b) harmonijski spektar toka zavojnice / harmonic spectrum of coil flux

Slika 2 — Primjer ustaljenog stanja s neparnim višim harmonicima

Figure 2 — Example of odd higher harmonic steady state



a) valni oblik toka zavojnice / waveform of coil flux

b) harmonijski spektar toka zavojnice / harmonic spectrum of coil flux

Slika 3 — Primjer ustaljenog stanja s parnim i neparnim višim harmonicima

Figure 3 — Example of even and odd higher harmonic steady state

— podharmonijska ferorezonancija rezultira ustaljenim stanjem koje sadrži jedan od podharmonika k i njegove višekratnike:

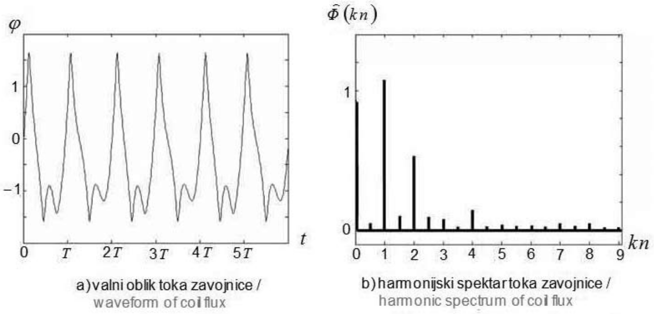
— subharmonic ferroresonance results in a steady-state which contains a subharmonic k and its multiples:

$$\varphi = \sum_n \hat{\Phi}(kn) \cdot \sin(kn\omega t + \alpha_{kn}), \quad n = 0,\ 1,\ 2,\ 3,\ \ldots,\ 1/k = 2,\ 3,\ 4,\ 5,\ \ldots \qquad (3)$$

S obzirom na najmanji podharmonik k u harmonijskom sadržaju varijable stanja, nastalo ustaljeno stanje naziva se $1/k$-struko periodičko ustaljeno stanja (slike 4 i 5). Promjena ustaljenog stanja s najmanjim podharmonikom k u ustaljeno stanje

Regarding the smallest subharmonic k in a harmonic content of a state-variable, the resulting steady state is called period-$1/k$ steady state (Figures 4 and 5). The change from a steady state with the lowest subharmonic k into a steady state s najmanjim podharmonikom $k/2$ naziva se udvostručenje periode.

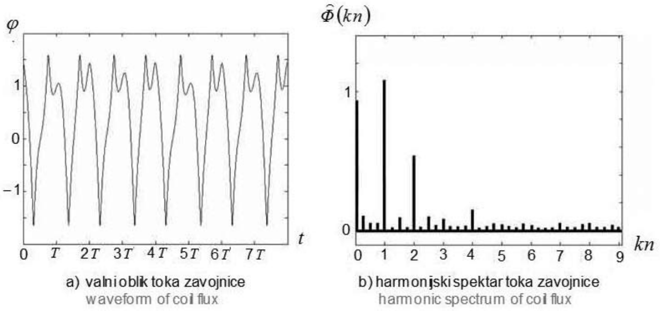
with the lowest subharmonic $k/2$ is called period-doubling.



a) valni oblik toka zavojnice / waveform of coil flux

b) harmonijski spektar toka zavojnice / harmonic spectrum of coil flux

Slika 4 — Primjer ustaljenog stanja s podharmonicima (dvostruko periodičko ustaljeno stanje)
Figure 4 — Example of subharmonic steady state (period-2 steady state)



a) valni oblik toka zavojnice
waveform of coil flux

b) harmonijski spektar toka zavojnice
harmonic spectrum of coil flux

Slika 5 — Primjer ustaljenog stanja s podharmonicima (četverostruko periodičko ustaljeno stanje)
Figure 5 — Example of subharmonic steady state (period-4 steady state)

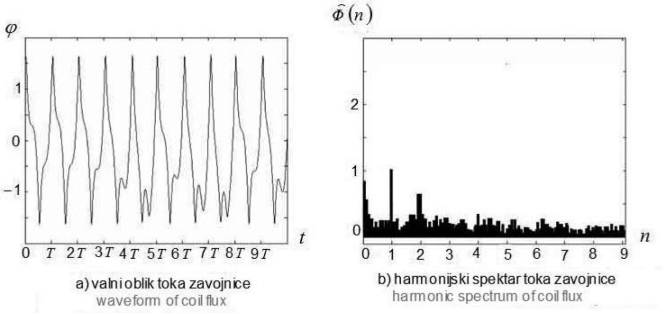
— kaotična ferorezonancija rezultira ustaljenim stanjem kontinuiranog harmonijskog spektra [5]:

— chaotic ferroresonance results in a steady state which has a continuous harmonic spectrum [5]:

$$\varphi = \int_{n=0}^{\infty} \hat{\Phi}(n)\cdot \sin\left(n\omega t + \alpha_n\right)\mathrm{d}\,n, \qquad (4)$$

tj. oscilacije se čine stohastičkim (slika 6).

i.e. the oscillations appear to be random (Figure 6).



a) valni oblik toka zavojnice
waveform of coil flux

b) harmonijski spektar toka zavojnice
harmonic spectrum of coil flux

Slika 6 — Primjer kaotičnog ustaljenog stanja
Figure 6 — Example of chaotic steady-state

Zajedničko svojstvo svih ustaljenih stanja nastalih spomenutim vrstama ferorezonancije jest visoki napon transformatora ferorezonantnog dijela elektroenergetske mreže. Pritom napon može biti nekoliko puta veći od nazivnog napona.

2 PRIMJER FEROREZONANTNOG DIJELA ELEKTROENERGETSKE MREŽE

Slika 7 prikazuje jednopolni dijagram ferorezonantnog dijela elektroenergetske mreže u kojemu je faza trofaznog transformatoru u praznom hodu, tj. nelinearna zavojnica, napajana preko kapaciteta lučne komore prekidača. Elektroenergetska mreža prikazana na slici 7 jednaka je 230 kV-tnoj transformatorskoj stanici Dorsey u kojoj se pojavila ferorezonancija, kao što je opisano u [6] do [8].

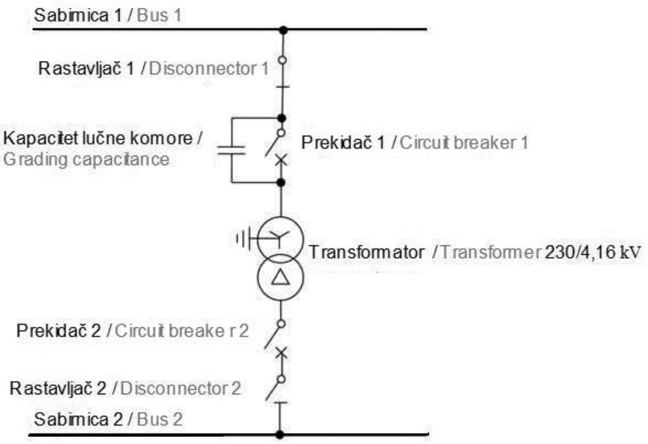
Ova je transformatorska stanica odabrana za analizu, jer su vrijednosti parametara značajnih za ferorezonanciju poznate za tu stanicu [8], za razliku od transformatorskih stanica elektroenergetske mreže Hrvatske i većine transformatorskih stanica općenito.

A common property of all steady states resulting from the mentioned types of ferroresonance is the high transformer voltage of a ferroresonant part of the electrical power network. Thereby, the voltage can be a few times higher than the nominal transformer voltage.

2 EXAMPLE OF A FERRORESONANT PART OF ELECTRICAL NETWORK

Figure 7 shows the single-line diagram of a ferroresonant part of the electrical power network in which the phase of an unloaded three-phase transformer, as a nonlinear coil, is fed through a grading capacitance of a circuit breaker. The electrical power network shown in Figure 7 is equivalent to the Manitoba Hydro's 230 kV Dorsey Converter Station in which the ferroresonance has occurred, as it is described in [6] to [8].

This station is chosen for the analysis, because the parameter values of importance for the ferroresonance are known for this station [8], unlike the converter stations of electrical power network in Croatia and unlike most of the converter stations in general.



Slika 7 — Ferorezonantni dio elektroenergetske mreže
Figure 7 — Ferroresonant part of electrical power network

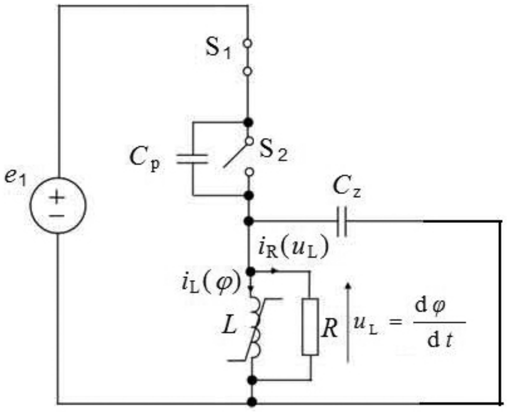
Za ferorezonantni dio elektroenergetske mreže prikazan na slici 7 ferorezonancija se može pojaviti u svakoj fazi sklapanjem polova prekidača 1. Primjerice, ako je pol rastavljača 1 faze 1 uklopljen i pol prekidača 1 u istoj fazi isklopljen, faza je transformatora napajana kroz kapacitet lučne komore prekidača 1. Pritom su svi polovi prekidača 2 i rastavljača 2 isklopljeni, tj. transformator je u praznom hodu. Stoga je cijeli se-

For the ferroresonant part of the electrical power network shown in Figure 7, the ferroresonance can occur in each phase by switching of poles of the circuit breaker 1. For instance, if the pole of the disconnector 1 in phase 1 is closed and the pole of the circuit breaker in the same phase is open, the phase of the transformer is fed through a grading capacity of the circuit breaker 1. Thereby, all the poles of circuit breaker 2 and disconnector 2 kundarni krug, koji se sastoji od sekundarnih namota trofaznog transformatora, prekidača 2, rastavljača 2 i sabirnice 2, zanemariv u daljnjoj analizi.

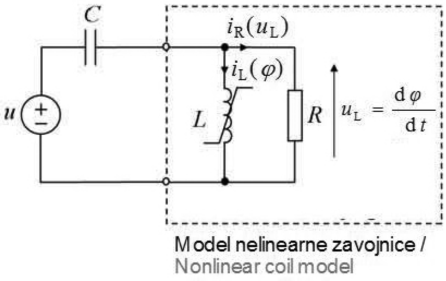
Slika 8 prikazuje model faze 1 elektroenergetske mreže prikazane na slici 7. Nelinearni induktivitet opisan funkcijom $i_L(\varphi)$ i paralelni otpor opisan funkcijom $i_R(u_L)$ predstavljaju zavojnicu sa željeznom jezgrom faze 1 transformatora u praznom hodu, gdje su i_L i φ struja i tok induktiviteta, a i_R i u_L struja i napon otpora. Ukupni gubici u željezu, pri čemu je zanemaren utjecaj viših harmonika, modelirani su linearnim otporom. Pritom je zanemarena magnetska veza između faza trofaznog transformatora, tj. trofazni je transformator modeliran kao tri jednofazna transformatora. C_p je kapacitet lučne komore prekidača, a C_z je ukupni dozemni kapacitet, uključujući kapacitet voda i međukapacitet zavoja namota transformatora. Idealni izvor napajanja e_1 predstavlja napon faze 1. Polovi prekidača 1 i rastavljača 1 faze 1 modelirani su sklopkama S_1 i S_2.

are open, i.e. the transformer is unloaded. Thus, the entire secondary circuit, being composed of secondary windings of the three-phase transformer, circuit breaker 2, disconnector 2 and bus 2, is negligible for the further analysis.

Figure 8 shows a model of phase 1 of the electrical power network shown in Figure 7. A nonlinear inductance described by the function $i_L(\varphi)$ and a parallel resistance described by the function $i_R(u_L)$ represent the iron core coil of the unloaded phase 1 of power transformer, where i_L and φ are the current and flux of inductance, i_R and u_L are the current and voltage of the resistance. Total iron-core losses, disregarding the effects of higher harmonics, are modelled by the linear resistance. Thereby, the paper disregards the magnetic coupling between the phases in a three-phase transformer, i.e. the three phase transformer is modelled as three single-phase transformers. C_p is the circuit breaker grading capacitance and C_z is the total phase-to-earth capacitance, including busbar capacitance to earth and transformer winding capacitance. An ideal source equivalent e_1 represents the system voltage of phase 1. Poles of the circuit breaker 1 and disconnector 1 of phase 1 are modelled as switches S_1 and S_2, respectively.



Slika 8 — Model ferorezonantnog dijela elektroenergetske mreže
Figure 8 — Model of the ferroresonant part of electrical power network



Slika 9 — Ferorezonantni krug
Figure 9 — Ferroresonant circuit

Slika 9 prikazuje ekvivalentni krug – ferorezonantni krug. Jednadžbe stanja ferorezonantnog kruga su:

The Figure 9 shows the equivalent circuit, named here as the ferroresonant circuit. The state-equations of the ferroresonant circuit are:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \dot{\varphi} = -u_\mathrm{C} + u, \tag{5a}$$

$$\frac{\mathrm{d}u_\mathrm{C}}{\mathrm{d}t} = \dot{u}_\mathrm{C} = \frac{1}{RC}(u - u_\mathrm{C}) + \frac{1}{C} i_\mathrm{L}(\varphi), \tag{5b}$$

gdje su:

where:

$$u = e_1 \frac{C_\mathrm{p}}{C_\mathrm{p} + C_\mathrm{Z}} = \hat{U} \sin \omega t, \tag{6a}$$

$$\hat{U} = \frac{C_\mathrm{p}}{C_\mathrm{p} + C_\mathrm{Z}} \hat{E}_1, \tag{6b}$$

$$C = C_\mathrm{p} + C_\mathrm{Z}. \tag{6c}$$

3 EKSPERIMENTALNI FEROREZONANTNI KRUG

Ferorezonancija može uništiti dijelove elektroenergetske mreže [6] do [10]. Stoga bi bilo preskupo istraživati ferorezonanciju na sâmim ferorezonantnim dijelovima elektroenergetske mreže, primjerice, mijenjajući vrijednosti parametara.

U svrhu kontroliranog istraživanja utjecaja vrijednosti parametara, bez opasnosti od uništenja komponenata, u laboratoriju je realiziran ferorezonantni krug koji se sastoji od linearnog kondenzatora $C = 20\ \mu\mathrm{F}$ i nelinearne zavojnice, slika 10. Krug je ovdje nazvan eksperimentalni ferorezonantni krug.

3 EXPERIMENTAL FERRORESONANT CIRCUIT

The ferroresonance can destroy parts of electrical power network [6] to [10]. Thus, it would be too expensive to investigate the ferroresonance on a ferroresonant part of electrical power network by varying its parameter values.

In order to investigate impact of parameter values in a controlled manner, without the danger of destruction of components, the ferroresonant circuit, being composed of the linear capacitor $C = 20\ \mu\mathrm{F}$ and the nonlinear coil, is realized in the laboratory, Figure 10. The circuit is named here as the experimental ferroresonant circuit.

Slika 10 — Eksperimentalni ferorezonantni krug
Figure 10 — Experimental ferroresonant circuit

Primarni namot toroidnog dvonamotnog transformatora sa željeznom jezgrom (Trafoperm N3) upotrijebljen je kao nelinearna zavojnica. Transformator je nazivne prividne snage $200\ \mathrm{VA}$ i nazivnog primarnog napona $30\ \mathrm{V}$.

Karakteristike nelinearnog induktiviteta:

The primary winding of the toroidal iron-cored (Trafoperm N3) two-winding transformer was used as a nonlinear coil. The transformer was designed for the nominal apparent power of $200\ \mathrm{VA}$ and for the nominal primary voltage of $30\ \mathrm{V}$.

The characteristics of nonlinear inductance

$$i_\mathrm{L}(\varphi)=\mathrm{sgn}(\varphi)\sqrt{0{,}1244\cdot\varphi^{2}+2{,}3\cdot10^{16}\cdot\varphi^{20}+4{,}93\cdot10^{31}\cdot\varphi^{38}}, \quad i_\mathrm{L},\ \mathrm{A}, \quad \varphi,\ \mathrm{Vs} \tag{7a}$$

i linearnog otpora

and linear resistance

$$i_\mathrm{R}(u_\mathrm{L})=u_\mathrm{L}/R, \tag{7b}$$

$$R=320\ \Omega, \tag{7c}$$

nelinearne zavojnice temelje se na rezultatima dobivenim standardnim ispitivanjem transformatora: na efektivnoj vrijednosti struje zavojnice kao funkciji efektivne vrijednosti napona zavojnice $I_\mathrm{T}(U_\mathrm{T})$ i na gubicima zavojnice kao funkciji efektivne vrijednosti napona zavojnice $P_\mathrm{T}(U_\mathrm{T})$ [11] i [12].

Autotransformator prividne snage 10 kVA upotrijebljen je kao promjenljivi naponski izvor u svim provedenim eksperimentima. Pritom je vršna vrijednost napona mijenjana u rasponu $0<\hat{U}<90,\ \mathrm{V}$.

Analizirani eksperimentalni ferorezonantni krug najjednostavniji je električki krug u kojemu je ferorezonancija moguća. Pritom su shema spoja i jednadžbe stanja eksperimentalnog ferorezonantnog kruga ekvivalentne shemi spoja prikazanoj na slici 9 i jednadžbama stanja (5).

Eksperimentalni ferorezonantni krug može biti fizički model ferorezonantnog dijela elektroenergetske mreže ako omogućuje istraživanje pojave značajne za original, tj. ako se mjerenjem na eksperimentalnom ferorezonantnom krugu identificiraju vrste ustaljenih stanja karakteristične za ferorezonanciju. Rezultati mjerenja prikazani su u 5 poglavlju.

U 4 poglavlju uspoređene su normirane vrijednosti parametara eksperimentalnog ferorezonantnog kruga i ferorezonantnog dijela elektroenergetske mreže. Time su utvrđene razlike normiranih vrijednosti parametara koje bi mogle imati utjecaj na razlike rezultata mjerenja dobivenih na eksperimentalnom ferorezonantnom krugu i transformatorskoj stanici Dorsey, na kojoj se eksperimentalni ferorezonantni krug, kao fizički model ferorezonantnog dijela elektroenergetske mreže, temelji.

of the nonlinear coil are based on the results obtained by the standard measurements: the RMS coil current as a function of RMS coil voltage $I_\mathrm{T}(U_\mathrm{T})$ and the coil loss as a function of RMS coil voltage $P_\mathrm{T}(U_\mathrm{T})$ [11] and [12].

The autotransformer of 10 kVA nominal apparent power was used as a variable voltage source in all the experiments. Thereby, the peak voltage value was varied in the range of $0<\hat{U}<90,\ \mathrm{V}$.

The analyzed experimental ferroresonant circuit is the simplest electrical circuit in which ferroresonance can occur. Thereby, the circuit scheme and state equations of the experimental ferroresonant circuit are equivalent to the circuit scheme shown in Figure 9 and state-equations (5), respectively.

The experimental ferroresonant circuit can be a physical model of the ferroresonant part of the electrical power network if it enables an investigation of a phenomenon that is important for the original, i.e. if it is possible to identify steady-state types that are characteristic for ferroresonance using the results of measurements carried out on the experimental ferroresonant circuit. Results of the measurement are presented in Section 5.

The per-unit values of parameters of the experimental ferroresonant circuit and ferroresonant part of the electrical power network, respectively, are compared in Section 4. In this way, the disagreement is determined between the per-unit values that could have an impact on the disagreement of measurement results obtained at the experimental ferroresonant circuit and Converter Station Dorsey, on which the experimental ferroresonant circuit is based as a physical model of the ferroresonant part of the electrical power network.

4 NORMIRANI PARAMETRI

Normirane varijable i parametri izraženi su s obzirom na referentne (bazne) vrijednosti napona, snage, frekvencije i struje:

4 PER-UNIT PARAMETERS

Per-unit variables and parameters are expressed in relation to reference quantities of voltage, power, frequency and current:

$$U_{\mathrm{ref}}, S_{\mathrm{ref}}, \omega_{\mathrm{ref}}, I_{\mathrm{ref}} = \frac{S_{\mathrm{ref}}}{U_{\mathrm{ref}}}. \tag{8}$$

Normirane konstitutivne relacije elemenata ferorezonantnog kruga prikazanog na slici 9 jesu:

Per-unit constitutive relations of elements of a ferroresonant circuit shown in Figure 9 are:

$$\bar{u} = \bar{\hat{U}} \sin \frac{\omega}{\omega_{\mathrm{ref}}} \tau, \quad \bar{\hat{U}} = \frac{\hat{U}}{U_{\mathrm{ref}}}, \quad \tau = \omega_{\mathrm{ref}} \cdot t, \tag{9a}$$

$$\bar{i}_{\mathrm{C}} = \bar{C} \frac{\mathrm{d}\bar{u}_{\mathrm{C}}}{\mathrm{d}\tau}, \quad \bar{C} = C \frac{U_{\mathrm{ref}} \cdot \omega_{\mathrm{ref}}}{I_{\mathrm{ref}}}, \tag{9b}$$

$$\bar{u}_{\mathrm{R}} = \bar{R} \cdot \bar{i}, \quad \bar{R} = R \frac{I_{\mathrm{ref}}}{U_{\mathrm{ref}}}, \tag{9c}$$

$$\bar{i}_{\mathrm{L}} = \bar{f}(\bar{\varphi}), \quad \bar{f}(\bar{\varphi}) = \frac{1}{I_{\mathrm{ref}}} f\left(\frac{U_{\mathrm{ref}} \cdot \bar{\varphi}}{\omega_{\mathrm{ref}}}\right). \tag{9d}$$

Stoga su jednadžbe stanja normiranog ferorezonantnog kruga:

Thus, the state equations of the per-unit ferroresonant circuit are:

$$\dot{\bar{\varphi}} = -\bar{u}_{\mathrm{C}} + \bar{\hat{U}} \cdot \sin \tau, \tag{10a}$$

$$\dot{\bar{u}}_{\mathrm{C}} = \frac{1}{\bar{R}\bar{C}}\left(\bar{\hat{U}} \sin \tau - \bar{u}_{\mathrm{C}}\right) + \frac{1}{\bar{C}} \bar{i}_{\mathrm{L}}(\bar{\varphi}). \tag{10b}$$

4.1 Normirani parametri ferorezonantnog dijela elektroenergetske mreže

Kao što je već spomenuto u drugom poglavlju, ferorezonantni dio elektroenergetske mreže opisan u tom poglavlju ekvivalentan je 230 kV-tnoj transformatorskoj stanici Dorsey (Manitoba, Kanada). Pritom, prema [8], ferorezonancija se pojavila za sljedeće vrijednosti parametara stanice:

4.1 Per-unit parameters of a ferroresonant part of electrical power network

As already mentioned in Section 2, the ferroresonant part of the electrical power network described in that chapter is equivalent to the Manitoba Hydro's 230 kV Dorsey Converter Station. Thereby, according to [8], the ferroresonance occurred at the following parameter values of the transformer station Dorsey:

$$\begin{gathered}
\left.\begin{aligned}
C_{\mathrm{p}} &\approx 6{,}6 \ \ \mathrm{nF} \\
C_{\mathrm{Z}} &\approx 12{,}5 \ \ \mathrm{nF} \\
\hat{E}_1 &= 188 \ \ \mathrm{kV}
\end{aligned}\right\} \rightarrow \left\{\begin{aligned}
\hat{U} &= \frac{C_{\mathrm{p}}}{C_{\mathrm{p}} + C_{\mathrm{Z}}} \hat{E}_1 = 65 \ \ \mathrm{kV} \\
C &= C_{\mathrm{p}} + C_{\mathrm{Z}} = 19{,}1 \ \ \mathrm{nF}
\end{aligned}\right. \\
\omega = 2\pi \cdot 60 \ \ \mathrm{Hz} \\
u_{\mathrm{R}} = R \cdot i, \quad R = 3{,}11 \ \ \mathrm{M\Omega} \\
i_{\mathrm{L}} = 1{,}43 \cdot 10^{-4} \varphi + 7{,}2 \cdot 10^{-37} \varphi^{13}, \quad i_{\mathrm{L}}, \mathrm{A}, \quad \varphi, \mathrm{Vs}\ .
\end{gathered} \tag{11}$$

Izraženo s obzirom na referentne vrijednosti:

Expressed in relation to reference quantities

$$\begin{aligned} U_{\mathrm{ref}} &= 188 \ \ \mathrm{kV}, \\ S_{\mathrm{ref}} &= 6{,}7 \ \ \mathrm{MVA}, \\ \omega_{\mathrm{ref}} &= 60 \ \ \mathrm{Hz}, \end{aligned} \tag{12}$$

normirani parametri ferorezonantnog dijela transformatorske stanice Dorsey su:

the per-unit parameters of the ferroresonant part of the Dorsey transformer station are:

$$\bar{u} = \bar{\hat{U}} \sin \tau, \quad \bar{\hat{U}} = 0{,}35, \quad \tau = \omega_{\mathrm{ref}} \cdot t, \tag{13a}$$

$$\bar{i}_{\mathrm{C}} = \bar{C} \frac{\mathrm{d}\bar{u}_{\mathrm{C}}}{\mathrm{d}\tau}, \quad \bar{C} = 0{,}04, \tag{13b}$$

$$\bar{u}_{\mathrm{R}} = \bar{R} \cdot \bar{i}, \quad R = 588 \tag{13c}$$

$$\bar{i}_{\mathrm{L}} = 0{,}002 \cdot \bar{\varphi} + 0{,}0024 \cdot \bar{\varphi}^{13}. \tag{13d}$$

4.2 Normirani parametri eksperimentalnog ferorezonantnog kruga

Vrijednosti parametara eksperimentalnog ferorezonantnog kruga su:

4.2 Per-unit parameters of the experimental ferroresonant circuit

The values of parameters of the experimental ferroresonant circuit are:

$$\begin{aligned} & u = \hat{U} \sin \omega t, \quad 0 \ \ \mathrm{V} < \hat{U} < 90 \ \ \mathrm{V}, \quad \omega = 2\pi \cdot 60 \ \ \mathrm{Hz}, \\ & i_{\mathrm{C}} = C \frac{\mathrm{d}u_{\mathrm{C}}}{\mathrm{d}t}, \quad C = 20 \ \ \mu\mathrm{F}, \\ & u_{\mathrm{R}} = R \cdot i, \quad R = 320 \ \ \Omega, \\ & i_{\mathrm{L}} = \mathrm{sgn}(\varphi) \sqrt{0{,}1244 \cdot \varphi^{2} + 2{,}3 \cdot 10^{16} \cdot \varphi^{20} + 4{,}93 \cdot 10^{31} \cdot \varphi^{38}} \end{aligned} \tag{14}$$

Izraženo s obzirom na referentne vrijednosti:

Expressed in relation to reference quantities

$$\begin{aligned} U_{\mathrm{ref}} &= 29 \ \ \mathrm{V}, \\ S_{\mathrm{ref}} &= 90 \ \ \mathrm{VA}, \\ \omega_{\mathrm{ref}} &= 50 \ \ \mathrm{Hz}, \end{aligned} \tag{15}$$

normirani parametri eksperimentalnog ferorezonantnog kruga su:

that is, in a per-unit system, the parameters of the experimental ferroresonant circuit are:

$$\bar{u} = \bar{\hat{U}} \sin \tau, \quad 0 < \bar{\hat{U}} < 3{,}1, \quad \tau = \omega_{\mathrm{ref}} \cdot t, \tag{16a}$$

$$\bar{i}_{\mathrm{C}} = \bar{C} \frac{\mathrm{d}\bar{u}_{\mathrm{C}}}{\mathrm{d}\tau}, \quad \bar{C} = 0{,}06, \tag{16b}$$

$$\bar{u}_{\mathrm{R}} = \bar{R} \cdot \bar{i}, \quad \bar{R} = 34{,}2, \tag{16c}$$

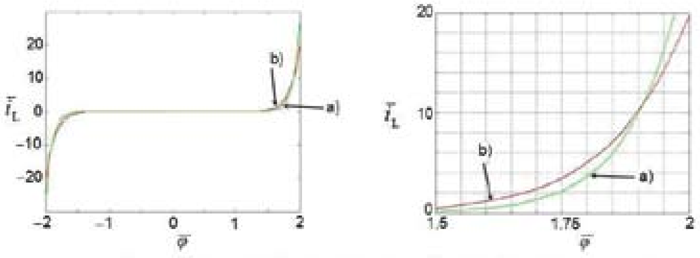
$$\bar{i}_{\mathrm{L}} = \mathrm{sgn}(\bar{\varphi}) \sqrt{1{,}1 \cdot 10^{-4} \cdot \bar{\varphi}^{2} + 4{,}82 \cdot 10^{-6} \cdot \bar{\varphi}^{20} + 2{,}44 \cdot 10^{-9} \cdot \bar{\varphi}^{38}} \ . \tag{16d}$$

4.3 Usporedba normiranih parametara

Usporedbom normiranih vrijednosti (13) i (16) razlika između vrijednosti normiranih otpora, (13c) i (16c), pokazuje se najznačajnijom. Pritom su karakteristike normiranih induktiviteta uspoređene samo za praktički mogući raspon vrijednosti toka, $|\overline{\varphi}| \leq 2$. Iz prikaza na slici 11 može se zaključiti da su, za navedeni raspon vrijednosti toka, razlike karakteristika zanemarive.

4.3 Comparison of per-unit parameters

By comparison of per-unit values (13) and (16), respectively, the difference between the values of per-unit resistances, (13c) and (16c) appears to be the significant one. Thereby, the characteristics of per-unit inductance are compared for a practically possible range of flux values, $|\overline{\varphi}| \leq 2$, only. From the depictions in Figure 11 it can be concluded that the disagreement between the characteristics, for the mentioned range of flux values, is negligible.



a) normirani induktivitet eksperimentalnog ferorezonantnog kruga / per-unit inductance of experimental ferroresonance circuit

b) normirani induktivitet transformatorske stanice Dorsey / per-unit inductance of Dorsey Converter Station

Slika 11 — Karakteristike normiranih induktiviteta $\bar{i}_L(\overline{\varphi})$ za praktički mogući raspon vrijednosti toka

Figure 11 — Characteristics of per-unit inductance $\bar{i}_L(\overline{\varphi})$ for a practically possible range of flux values

Normirani otpor je u eksperimentalnom ferorezonantnom krugu značajno manji od otpora u transformatorskoj stanici Dorsey. Dakle, normirani gubici u eksperimentalnom ferorezonantnom krugu veći su od gubitaka u transformatorskoj stanici Dorsey. Utjecaj odstupanja vrijednosti normiranih otpora utvrdit će se usporedbom rezultata mjerenja izvršenih na eksperimentalnom ferorezonantnom krugu i transformatorskoj stanici Dorsey, na kojoj se eksperimentalni ferorezonantni krug temelji.

The per-unit resistance in the experimental ferroresonant circuit is significantly lower than the one in Dorsey Converter Station. Consequently, the per-unit losses in the experimental ferroresonant circuit are higher than in the Dorsey Converter Station. The impact of the deviation of per-unit resistance values will be determined by comparison of the results of the measurements carried out on the experimental ferroresonant circuit and on the Dorsey Converter Station, on which the experimental ferroresonant circuit is based.

5 REZULTATI MJERENJA

Kao što je već spomenuto, praktički je nemoguće istraživati ferorezonanciju na sâmim ferorezonantnim dijelovima elektroenergetske mreže, tj. na transformatorskoj stanici Dorsey, mijenjanjem vrijednosti parametara stanice. Dakle, kao jedini rezultat mjerenja na transformatorskoj stanici Dorsey može se upotrijebiti primijećenu pojavu ferorezonancije za vrijednosti parametara (13).

Mjerenja na eksperimentalnom ferorezonantnom krugu sa vrijednostima parametara (16) provedena su, u Laboratoriju za energetsku elektroniku na Elektrotehničkom fakultetu Osijek, u svrhu identifikacije pojave ferorezonancije i utvrđivanja utjecaja odstupanja vrijednosti

5 RESULTS OF THE MEASUREMENTS

As already said, it is practically impossible to investigate the ferroresonance on a ferroresonant part of electrical power network, i.e. on the Dorsey Converter Station, by varying its parameter values. Consequently, we can take the noticed occurrence of ferroresonance for given parameter values (13) as the only result of the measurements on the Dorsey Converter Station.

The measurements on the experimental ferroresonant circuit with given parameter values (16) are carried out in the Laboratory for Power Electronics at the Faculty of Electrical Engineering Osijek in order to identify the occurrence of ferroresonance and to determine the impact of deviation of per-unit resistance normiranih otpora (13c) i (16c). Na taj način će eksperimentalni ferorezonantni krug biti vrednovan kao fizički model ferorezonantnog dijela elektroenergetske mreže. Pritom, kao što je već spomenuto u 3 poglavlju, eksperimentalni ferorezonantni krug može biti fizički model ferorezonantnog dijela elektroenergetske mreže ako se mjerenjem na eksperimentalnom ferorezonantnom krugu identificiraju vrste ustaljenih stanja karakteristične za ferorezonanciju.

Vrste ustaljenih stanja identificirane su s pomoću harmonijskog spektra toka zavojnice φ. Harmonijski je spektar dobiven brzom Fourierovom transformacijom primijenjenom na 20 perioda T valnog oblika toka zavojnice φ, $T = 20$ ms. Pritom je valni oblik toka zavojnice φ izračunat, prema Faradayevom zakonu, kao integral mjerenog napona zavojnice u_L. Vrijednosti napona zavojnice u_L uzorkovani su i pohranjeni s pomoću osciloskopa Tektronix TDS3012B. Valni oblik toka zavojnice φ, kao integral pohranjenih vrijednosti napona zavojnice u_L, i harmonijski spektar toka zavojnice φ izračunati su s pomoću Matlaba 7.0.

Tijekom mjerenja je jedini promjenljivi parametar vršna vrijednost napona napajanja $\hat{U}$ (16a). Kao što je prikazano u tablici 1, povećanjem vršne vrijednosti napona napajanja, ferorezonantni skok pojavio se za vrijednost $\hat{U}\approx 1{,}1$. Daljnjim povećanjem vršne vrijednosti napona napajanja viljuškasta bifurkacija, podharmonijska i kaotična ferorezonancija identificirane su za vršne vrijednosti napona napajanja $\hat{U}=1{,}4$, $\hat{U}\approx 2{,}4$ i $\hat{U}\approx 2{,}7$. Smanjenjem vršne vrijednosti napona napajanja reverzni se ferorezonantni skok pojavio za vršnu vrijednost napona napajanja $\hat{U}\approx 0{,}75$. Dakle, u rasponu vrijednosti $0{,}75 \le \hat{U} \le 1{,}1$, ferorezonancija se može pojaviti ovisno o vrijednostima početnih uvjeta [13]. U nastavku teksta će se raspon vršnih vrijednosti napona napajanja u kojemu pojava ferorezonancije ovisi o početnim uvjetima nazivati ferorezonantni raspon. Slike 12 prikazuju valne oblike i harmonijske spektre toka zavojnice dobivene mjerenjem. Slika 13 prikazuje bifurkacijski dijagram dobiven mjerenjem [14].

U transformatorskoj stanici Dorsey ferorezonancija osnovne frekvencije pojavila se za vrijednost $\hat{U}\approx 0{,}35$. Budući da mjerenja na sâmoj transformatorskoj stanici nisu moguća, u sljedećem će se poglavlju ferorezonantni raspon matematičkog modela transformatorske stanice Dorsey, (10) i (13), odrediti simulacijom. Usto će biti određene vrste ustaljenih stanja dobivene povećavanjem i smanjenjem vršnih vrijednosti napona napajanja u rasponu $0 < \hat{U} \le 3{,}1$. Ferorezonantni raspon i vrste ustaljenih stanja bit će određene simulacijom i za matematički model eksperimentalnog ferorezonantnog kruga, (10) i (16).

values, (13c) and (16c). In this way, the experimental ferroresonant circuit will be evaluated as a physical model of a ferroresonant part of the electrical power network. Thereby, as already mentioned in Section 3, the experimental ferroresonant circuit can be a physical model of the ferroresonant part of the electrical power network if it is possible to identify steady-state types that are characteristic for ferroresonance using the results of the measurements carried out on the experimental ferroresonant circuit.

Steady-state types are identified using the harmonic spectrum of the inductor flux φ. The harmonic spectrum is obtained using the fast Fourier transformation that is applied to 20 periods T of the inductor flux φ, $T = 20$ ms. Thereby, the waveform of the inductor flux φ is calculated, according to the Faraday's law, as an integral of the measured inductor voltage u_L. The values of inductor voltage u_L were sampled and stored using the Tektronix TDS3012B oscilloscope. The waveform of the inductor flux φ, as an integral of the stored values of inductor voltage u_L, and its harmonic spectrum are calculated using Matlab 7.0.

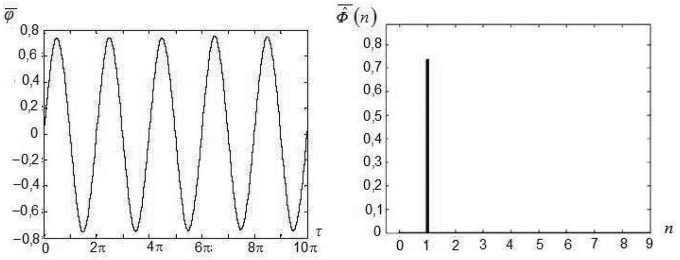
During the measurements, the only variable parameter was the peak value of source voltage $\hat{U}$ (16a). As it is shown in Table 1, by increasing the peak value of source voltage, the ferroresonant jump occurred at the value of $\hat{U}\approx 1{,}1$. By further increasing the peak value of source voltage pitchfork bifurcation, subharmonic and chaotic ferroresonance are identified at peak values of source voltage of $\hat{U}=1{,}4$, $\hat{U}\approx 2{,}4$ and $\hat{U}\approx 2{,}7$, respectively. By decreasing the peak value of the source voltage, reverse ferroresonant jump occurred at the peak value of source voltage $\hat{U}\approx 0{,}75$. Thus, in the range $0{,}75 \le \hat{U} \le 1{,}1$, ferroresonance can occur depending on the values of initial conditions [13]. In the rest of the paper, the range of peak values of source voltage in which initiation of ferroresonance depends on the values of initial conditions is called a ferroresonant range. Figures 12 show waveforms and harmonic spectra of coil flux obtained by measurements. Figure 13 shows the bifurcation diagram obtained by measurements [14].

At the Dorsey Converter Station, fundamental frequency ferroresonance occurred at the value of $\hat{U}\approx 0{,}35$. Because it is practically impossible to investigate the ferroresonance on the converter station, in next chapter, the ferroresonant range of the mathematical model of the Dorsey Converter Station, (10) and (13), will be determined by simulation. Thereby, steady-state types obtained by increasing and decreasing the peak value of source voltage inside the range $0 < \hat{U} \le 3{,}1$ will be determined. Ferroresonant range and steady-state types of the mathematical model of experimental ferroresonant circuit, (10) and (16), will be determined using the simulation as well.

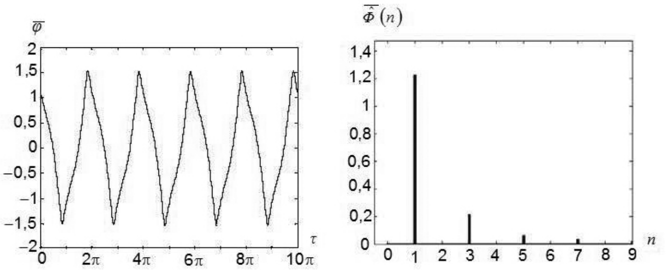
Tablica 1 – Vrste ustaljenih stanja i vrste ferorezonancija/bifurkacija eksperimentalnog ferorezonantnog kruga dobivene mjerenjem

Table 1 – Steady-state types and types of ferroresonance/bifurcations of the experimental ferroresonant circuit obtained by measurements

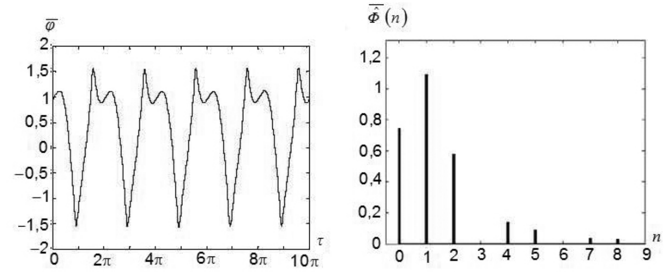
Povećanje / Increasing $\overline{\hat{U}}$, p.u.	Smanjenje / Decreasing $\overline{\hat{U}}$, p.u.	Ustaljena stanja i bifurkacije / Steady-states and bifurcations
$0 < \overline{\hat{U}} < 1,1$	$0 < \overline{\hat{U}} < 0,75$	Jednoharmonijsko ustaljeno stanje / Monoharmonic steady-state
$\overline{\hat{U}} = 1,1$	-	Ferorezonantni skok (ferorezonancija osnovne frekvencije) / Ferroresonant jump (fundamental frequency ferroresonance)
-	$\overline{\hat{U}} = 0,75$	Reverzni ferorezonantni skok / Reverse ferroresonant jump
$1,1 < \overline{\hat{U}} < 1,4$	$0,75 < \overline{\hat{U}} < 1,4$	Ustaljeno stanje s neparnim višim harmonicima / Odd higher harmonic steady-state
$\overline{\hat{U}} = 1,4$		Viljuškasta bifurkacija / Pitchfork bifurcation
$1,4 < \overline{\hat{U}} < 2,4$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$\overline{\hat{U}} = 2,4$		Podharmonijska ferorezonancija (udvostručenje periode) / Subharmonic frequency ferroresonance (period-doubling)
$2,4 < \overline{\hat{U}} < 2,7$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$\overline{\hat{U}} = 2,7$		Kaotična ferorezonancija / Chaotic ferroresonance
$2,7 < \overline{\hat{U}} \leq 3,1$		Kaotično ustaljeno stanje / Chaotic steady-state



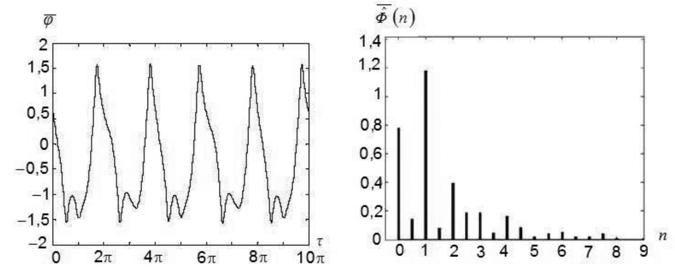
a) Jednoharmonijsko ustaljeno stanje dobiveno za / Monoharmonic steady-state obtained at $\overline{\hat{U}} = 0,73$



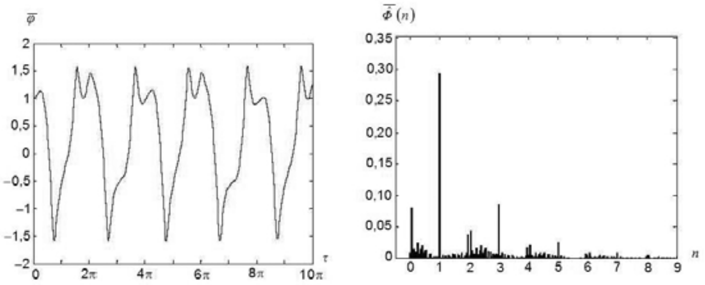
b) Ustaljeno stanje s neparnim višim harmonicima dobiveno za / Odd higher harmonic steady-state obtained at $\overline{\hat{U}} = 1,22$



c) Ustaljeno stanje s parnim i neparnim višim harmonicima dobiveno za /
Even and odd higher harmonic steady-state obtained at
$\hat{\overline{U}} = 1,95$

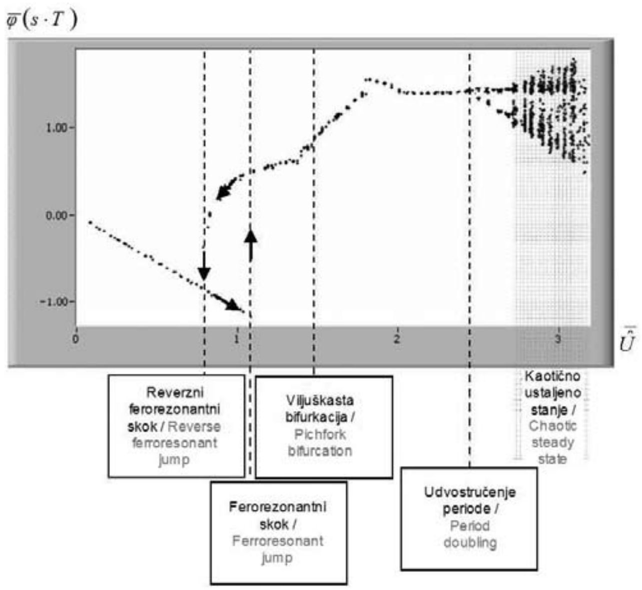


d) Ustaljeno stanje s podharmonicima (dvostruko periodičko ustaljeno stanje) dobiveno za /
Subharmonic steady-state (period-two steady-state) obtained at
$\hat{\overline{U}} = 2,58$



e) Kaotično ustaljeno stanje dobiveno za
Chaotic steady-state obtained at
$\hat{\overline{U}} = 2,95$

Slika 12 — Valni oblici i harmonijski spektri toka zavojnice dobiveni mjerenjem
Figure 12 — Waveforms and harmonic spectra of coil flux obtained by measurements



Slika 13 — Bifurkacijski dijagram dobiven mjerenjem ($s = 50, 51, ..., 99, 100$)
Figure 13 — Bifurcation diagram obtained by measurements ($s = 50, 51, ..., 99, 100$)

6 REZULTATI SIMULACIJE

Matematički modeli transformatorske stanice Dorsey, (10) i (13), i eksperimentalnog ferorezonantnog kruga, (10) i (16), realizirani su u Matlab Simulinku. Kao metoda numeričke integracije odabrana je Dormand-Prince metoda s promjenljivim korakom integracije [15].

U tablicama 2 i 3 prikazana su ustaljena stanja dobivena povećanjem i smanjenjem vršnih vrijednosti napona napajanja u rasponu $0 < \hat{U} \leq 3{,}1$. Pritom je ferorezonantni raspon transformatorske stanice Dorsey $(0{,}05 \leq \hat{U} \leq 0{,}95)$ značajno širi od ferorezonantnog raspona eksperimentalnog ferorezonantnog kruga $(0{,}75 \leq \hat{U} \leq 1{,}13)$, tj. ferorezonancija je moguća za značajno manje vršne vrijednosti napona napajanja u transformatorskoj stanici Dorsey.

Vrste ustaljenih stanja dobivene za vršne vrijednosti napona napajanja veće od onih u ferorezonantnom rasponu značajno se razlikuju u transformatorskoj stanici Dorsey, tablica 2, i eksperimentalnom ferorezonantnom krugu, tablica 3. Međutim, jedina značajna razlika između ferorezonantnih vrsta ustaljenih stanja jest gustoća harmonijskog spektra, slike 2-6, koja ima praktički zanemariv značaj u odnosu na značaj vršnih vrijednosti varijabli stanja koje mogu biti vrlo visoke. Stoga, u nastavku teksta razlika ferorezonantnih ustaljenih stanja bit će zanemarena te će razlika ferorezonantnih raspona biti smatrana jedinom značajnom razlikom.

6 SIMULATION RESULTS

The mathematical models of the Dorsey Converter Station, (10) and (13), and the experimental ferroresonant circuit, (10) and (16), are realized using the software package MATLAB/Simulink. Dormand-Prince method with variable integration step is used as a numerical integration method [15].

Tables 2 and 3 show steady-states obtained by increasing and decreasing the peak values of the source voltage in the range $0 < \hat{U} \leq 3{,}1$. Thereby, the ferroresonant range of the Dorsey Converter Station $(0{,}05 \leq \hat{U} \leq 0{,}95)$ is significantly wider than the ferroresonant range of the experimental ferroresonant circuit $(0{,}75 \leq \hat{U} \leq 1{,}13)$, i.e. ferroresonance is possible for a significantly lower peak values of source voltage at the Dorsey Converter Station.

The steady-state types obtained for peak values of source voltage that are higher than the ones in a ferroresonant range differ significantly at the Dorsey Converter Station, Table 2, and experimental ferroresonant circuit, Table 3. However, the only significant difference between the ferroresonant steady-state types is the density of their harmonic spectrum, Figures 2-6, which has negligible practical importance in comparison with the magnitudes of state variables that can be quite high. Therefore, in the rest of the paper the disagreement of ferroresonant steady-states will be disregarded and the disagreement of ferroresonant ranges will be taken as the only significant disagreement.

Tablica 2 – Vrste ustaljenih stanja transformatorske stanice Dorsey dobivene simulacijom
Table 2 – Steady-state types of the Dorsey Converter Station obtained by simulation.

Povećanje / Increasing $\bar{\hat{U}}$, p.u.	Smanjenje / Decreasing $\bar{\hat{U}}$, p.u.	Ustaljena stanja / Steady-states
$0 < \bar{\hat{U}} < 0,95$	$0 < \bar{\hat{U}} < 0,05$	Jednoharmonijsko ustaljeno stanje / Monoharmonic steady-state
$0,95 \leq \bar{\hat{U}} < 1,2$	$0,05 \leq \bar{\hat{U}} < 1,2$	Ustaljeno stanje s neparnim višim harmonicima / Odd higher harmonic steady-state
$1,2 \leq \bar{\hat{U}} < 1,62$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$1,62 \leq \bar{\hat{U}} < 1,73$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$1,73 \leq \bar{\hat{U}} < 1,75$		Kaotično ustaljeno stanje / Chaotic steady-state
$1,75 \leq \bar{\hat{U}} < 1,85$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$1,85 \leq \bar{\hat{U}} < 1,9$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$1,9 \leq \bar{\hat{U}} < 2,0$		Kaotično ustaljeno stanje / Chaotic steady-state
$2,0 \leq \bar{\hat{U}} < 2,73$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$2,73 \leq \bar{\hat{U}} \leq 3,1$		Kaotično ustaljeno stanje / Chaotic steady-state

Tablica 3 – Vrste ustaljenih stanja eksperimentalnog ferorezonantnog kruga dobivene simulacijom
Table 3 – Steady-state types of experimental ferroresonant circuit obtained by simulation

Povećanje / Increasing $\bar{\hat{U}}$, p.u.	Smanjenje / Decreasing $\bar{\hat{U}}$, p.u.	Ustaljena stanja / Steady-states
$0 < \bar{\hat{U}} < 1,13$	$0 < \bar{\hat{U}} < 0,75$	Jednoharmonijsko ustaljeno stanje / Monoharmonic steady-state
$1,13 \leq \bar{\hat{U}} < 1,94$	$0,75 \leq \bar{\hat{U}} < 1,94$	Ustaljeno stanje s neparnim višim harmonicima / Odd higher harmonic steady-state
$1,94 < \bar{\hat{U}} < 2,64$		Ustaljeno stanje s parnim i neparnim višim harmonicima / Even and odd higher harmonic steady-state
$2,64 < \bar{\hat{U}} < 3,05$		Dvostruko periodičko ustaljeno stanje / Period-two steady-state
$3,05 < \bar{\hat{U}} \leq 3,1$		Kaotično ustaljeno stanje / Chaotic steady-state

Simulacija je provedena za sve kombinacije vrijednosti parametara (13) i (16) te je s pomoću utvrđenih ferorezonantnih raspona, tablica 4, zaključeno da je jedino razlika u vrijednostima otpora, (13c) i (16c), značajna.

Simulation is carried out for all combinations of parameter values (13) and (16) in order to obtain ferroresonant ranges, Table 4. From these results it can be concluded that the disagreement between the resistance values, (13c) and (16c), is the significant one.

Tablica 4 – Ferorezonantni rasponi dobiveni simulacijom
Table 4 – Ferroresonant ranges obtained by simulation

	$i_L(\varphi)$, (13d)		$i_L(\varphi)$, (16d)	
	C, (13b)	C, (16b)	C, (13b)	C, (16b)
R, (13c)	$0,05 \leq \bar{\hat{U}} \leq 0,95$	$0,04 \leq \bar{\hat{U}} \leq 1,0$	$0,05 \leq \bar{\hat{U}} \leq 0,83$	$0,04 \leq \bar{\hat{U}} \leq 0,95$
R, (16c)	$0,98 \leq \bar{\hat{U}} \leq 1,25$	$0,68 \leq \bar{\hat{U}} \leq 1,15$	$1,04 \leq \bar{\hat{U}} \leq 1,22$	$0,75 \leq \bar{\hat{U}} \leq 1,14$

Dakle, uzrok razlike ferorezonantnih raspona transformatorske stanice Dorsey i eksperimentalnog ferorezonantnog kruga jest razlika normiranih otpora $\overline{R}$, tj. normiranih gubitaka, eksperimentalnog ferorezonantnog kruga i transformatorske stanice Dorsey. Međutim, nije moguće realizirati eksperimentalni ferorezonantni krug s normiranim gubicima približno jednakim normiranim gubicima ferorezonantnog dijela elektroenergetske mreže. Prema [9, 16] veći gubici, kao u eksperimentalnom ferorezonantnom krugu, smanjuju ferorezonantni raspon, tj. vjerojatnost pojave ferorezonancije. Stoga, za pojavu ferorezonancije potrebno je napajati eksperimentalni ferorezonantni krug značajno većom vršnom normiranom vrijednošću napona napajanja nego u slučaju transformatorske stanice Dorsey.

Usto se zbog značajno manjih normiranih gubitaka u transformatorskoj stanici Dorsey ustaljeno stanje s parnim i neparnim višim harmonicima, dvostruko periodičko ustaljeno stanje i kaotično ustaljeno stanje pojavljuju na značajno manjim normiranim vršnim vrijednostima napona napajanja nego u eksperimentalnom ferorezonantnom krugu.

7 ZAKLJUČAK

Ferorezonancija je pojava koja može uništiti dijelove elektroenergetske mreže. Može se pojaviti u dijelovima elektroenergetske mreže koji sadrže nelinearnu zavojnicu sa željeznom jezgrom koja je napajana preko komponente ili dijela elektroenergetske mreže, kapacitivnost kojih nije zanemariva. Vrste ferorezonancije određene su harmonijskim spektrom varijable stanja u ustaljenom stanju nastalom ferorezonancijom.

Eksperimentalno istraživanje ferorezonancije na ferorezonantnim dijelovima elektroenergetske mreže nije moguće bez opasnosti od uništenja komponenata mreže. U svrhu kontroliranog istraživanja ferorezonancije, u laboratoriju je realiziran eksperimentalni ferorezonantni krug na temelju vrijednosti parametara 230 kV-ne transformatorske stanice Dorsey, kao fizički model ferorezonantnog dijela elektroenergetske mreže. Pritom je transformatorska stanica Dorsey odabrana jer su za tu stanicu poznate vrijednosti svih parametara značajnih za pojavu ferorezonancije.

Usporedbom normiranih parametara te rezultata mjerenja i simulacije eksperimentalnog ferorezonantnog kruga i 230 kV-ne transformatorske stanice Dorsey zaključeno je da se eksperimentalni ferorezonantni krug može upotrebljavati kao fizički model ferorezonantnog dijela elektroenergetske mreže. Pritom je nužno uzeti u obzir da su

Consequently, the cause for the disagreement of ferroresonant ranges of the Dorsey Converter Station and experimental ferroresonant circuit is the disagreement of per-unit resistance values $\overline{R}$, i.e. per-unit losses of the Dorsey Converter Station and experimental ferroresonant circuit. However, it is impossible to realize an experimental ferroresonant circuit with per-unit losses that would be approximately equal to the per-unit losses of a ferroresonant part of the electrical network. According to [9] and [16] higher losses, as the ones in the experimental ferroresonant circuit, decrease the ferroresonant range, i.e. the possibility of ferroresonance initiation. Therefore, in order to initiate the ferroresonance, it is necessary to feed the experimental ferroresonant circuit with significantly higher peak value of source voltage than in the case of the Dorsey Converter Station.

Furthermore, due to the significantly lower per-unit losses at the Dorsey Converter Station, even and odd higher harmonic steady state, period-two steady state and chaotic steady state occur at significantly lower peak values of source voltage than in the case of the experimental ferroresonant circuit.

7 CONCLUSIONS

Ferroresonance is a phenomenon which can destroy parts of the electrical power network. It can occur in a part of the electrical power network which comprises a nonlinear coil with an iron core that is fed through a component or a part of the electrical power network, the capacitance of which is not negligible. The types of ferroresonance are defined by the harmonic spectrum of the state variable in steady state which has arisen after the ferroresonance.

The experimental investigation of ferroresonance on ferroresonant parts of the electrical power network is not possible without the risk of destroying network components. In order to investigate ferroresonance in a controlled manner, an experimental ferroresonant circuit is set up in the laboratory based on parameter values of 230 kV Dorsey Converter Station, as a physical model of a ferroresonant part of the electrical power network. Therefore, the Dorsey Converter Station is chosen because all parameter values significant for the phenomenon of ferroresonance are known for this station.

Comparison of per-unit parameters and results of measurements and simulation of the experimental ferroresonant circuit and 230 kV Dorsey Converter Station implies that the experimental ferroresonant circuit can be used as the physinormirani gubici eksperimentalnog ferorezonantnog kruga značajno veći od normiranih gubitaka 230 kV-ne transformatorske stanice Dorsey.

Na opisani bi se način mogao realizirati fizički model ferorezonantnih dijelova hrvatske elektroenergetske mreže. Pritom bi najveći problem bilo dobivanje vrijednosti parametara mreže značajnih za pojavu ferorezonancije.

cal model of a ferroresonant part of the electrical power network. Therefore, it is necessary to take into account that the per-unit losses of the experimental ferroresonant circuit are significantly higher than the per-unit losses of the 230 kV Dorsey Converter Station.

In the described manner, a physical model of ferroresonant parts of the Croatian electrical power network could be realized. In doing so, the major difficulty would be obtaining those values of network parameters that are significant for the initiation of ferroresonance.

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TOČNIJI PRORAČUN MAGNETSKIH GUBITAKA U ASINKRONOM MOTORU

A MORE ACCURATE CALCULATION OF MAGNETIC LOSSES IN THE INDUCTION MOTOR

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U radu je načinjena usporedba rezultata izračuna gubitaka vrtložnih struja u zubima asinkronog motora analitičkom metodom i metodom konačnih elemenata. Uz pretpostavke da su permeabilnost i vodljivost lima konstantni, mogu se ukupni gubici vrtložnih struja računati kao zbroj pulzacijskih i površinskih gubitaka. Dane su upute kako se mogu računati ukupni gubici u zubima za sve oblike zuba uzimajući u obzir potiskivanje toka u limovima, prigušenje toka u zubima, te faktore obrade lima i paketa limova. Vrednovanje analitičkog modela izračuna gubitaka načinjeno je i usporedbom s mjerenjima.

The work presents a comparison of results of the calculation of eddy current losses in the induction motor teeth by virtue of the analytical method and the finite element method. Under the assumption that sheet permeability and conductivity are constant, total eddy current losses can be calculated as the aggregate of pulsation and surface losses. Instructions are given regarding the manner of calculation of total losses in the teeth for all teeth forms, taking into consideration the suppression of flows in the sheets, flow attenuation in the teeth and the sheet and sheet package processing factors. Valuation of the analytical model of loss calculation was also made by virtue of comparison with the measurements.

Ključne riječi: asinkroni motor; gubici histereze; gubici vrtložnih struja; metoda konačnih elemenata; površinski gubici; pulzacijski gubici
Key words: induction motor; finite element method; hysteresis losses; pulsation losses; surface losses

1 UVOD

Elektromotorni pogoni čine oko 70 % industrijskih trošila, pa se trend povećanja energetske korisnosti elektromotornih pogona, ne samo s ekonomskog već i s ekološkog stanovišta, posebno odrazio na proučavanje gubitaka asinkronih motora, koji su najzastupljeniji u tim pogonima. Bitnu komponentu koja utječe na energetsku korisnost asinkronih motora predstavljaju gubici energije u magnetskim materijalima. Gubici u statorskim i rotorskim paketima limova dijele se na osnovne gubitke, koji su uglavnom vezani uz temeljni harmonik indukcije u zračnom rasporu (gubici magnetiziranja), i na dodatne gubitke, koje uzrokuju viši ili niži harmonici indukcije u zračnom rasporu [1] i [2]. S obzirom na mjesta nastajanja osnovne i dodatne gubitke dijelimo na površinske gubitke u zubima, pulzacijske gubitke u zubima, te pulzacijske gubitke u jarmovima. Komponenta površinskih gubitaka obično se zanemaruje pri proračunu osnovnih gubitaka. Polje u asinkronim motorima je rotacijsko, pa se ipak smatra da gubici u zubima nastaju zbog izmjeničnog polja, dok se samo za gubitke u jarmovima smatra da nastaju zbog rotacijskog polja.

Raspodjela magnetskog polja električnih strojeva na mnogim mjestima je potpuno dvodimenzionalna i iskrivljena, pa je uobičajeno takvu raspodjelu magnetskog polja opisivati kao izobličeno eliptičko rotacijsko magnetsko polje. Zbog takvog kompliciranog mehanizma magnetiziranja, određivanje gubitaka u statorskim i rotorskim paketima limova asinkronih motora vrlo je teško izvesti analitičkim izračunima, jer se moraju napraviti određena zanemarivanja. Kao prvo, zbog nelinearnosti krivulje prvog magnetiziranja, pojave histereze i utjecaja obrade limova i paketa limova, proračun gubitaka u statorskim i rotorskim paketima limova ne može se provesti egzaktno. Nadalje, proračun otežava i složena geometrija limova i pojava površinskog učinka (skin efekta), a zbog nemogućnosti da se istodobno uračunaju svi navedeni utjecaji za točan proračun, u ovom će se radu istražiti samo utjecaj geometrije limova na gubitke vrtložnih struja u zubima. Konačno, ostali se utjecaji mogu uzeti u obzir naknadno s odgovarajućim faktorima, izborima odgovarajućih podataka (permeabilnost) i eksperimentalnim podacima (gubici histereze, obrada lima) [1], [3] i [4].

Tijekom posljednjih trideset godina razvoj numeričkih tehnika omogućio je da se rješavaju realistični numerički modeli kojima se može objasniti puno širi spektar problema nego korištenjem analitičkih metoda, koje su u pravilu ograničene na homogenost, linearnost i statična polja. Iz tog je razloga, u ovom radu analitički proračun

1 INTRODUCTION

Electromotor drives make up about 70 % of industrial use and so the trend of increase of energetic efficiency of electromotor drives, not only from the economic but also from the environmental standpoint, has an especially significant effect on the study of induction motor losses which are most present in these drives. Energy losses in magnetic materials represent an important component which influences the energetic efficiency of induction motors. Losses in the stator and rotor sheet metal packages are divided into basic losses, which are mostly related to the fundamental induction harmonic in the air gap (magnetizing losses), and additional losses caused by higher or lower induction harmonics in the air gap [1] and [2]. Depending on the locations where fundamental and additional losses occur, these are divided into surface losses in the teeth and the pulsation losses in the yokes. The surface losses component is usually disregarded at the calculation of fundamental losses. The field in induction motors is rotational, so it is considered nevertheless that losses in the teeth occur due to the alternate field, while the losses in the yokes are considered to be caused by the rotational field.

The distribution of the magnetic field of electric machines is two-dimensional and distorted in many places, so it is common practice to describe such distribution of the magnetic field as a distorted elliptic rotational magnetic field. Because of such a complicated magnetizing mechanism, the determination of losses in the stator and rotor sheet metal packages is very difficult to derive by analytic calculations because certain disregarding needs to be done. Firstly, due to the non-linearity of the first magnetizing curve, the occurrence of the hysteresis phenomenon and the influence of the processing of sheets and sheet packages, the calculation of losses in the stator and rotor sheet metal packages cannot be undertaken exactly. Furthermore, the undertaking of the calculation is additionally made difficult by the geometry of sheet metal and occurrences of the skin effect, and, because of the impossibility of simultaneous inclusion of all the mentioned influences for an accurate calculation, only the influence of the geometry on eddy current losses in the teeth will be studied in this work. Finally, the other influences may be taken into consideration afterwards with the adequate factors, choices of adequate data (permeability) and experimental data (hysteresis losses, sheet processing) [1], [3] and [4].

Over the last thirty years, the development of numerical techniques has enabled the resolution of realistic numerical models which may be used to explain a much broader spectre of problems than by the use of analytical methods which are usually limited to homogeneity, linearity and static fields.

gubitaka vrtložnih struja u zubima asinkronog motora vrednovan usporedbom s numeričkim rezultatima dobivenim metodom konačnih elemenata.

U radu su izvedeni izrazi za analitički proračun gubitaka. Međutim, iz razloga što se u dostupnoj literaturi [1], [2] i [3], bez dokaza da je to dopušteno, neovisno računaju površinski i pulzacijski gubici, potrebno je bilo dokazati da se površinski i pulzacijski gubici mogu računati neovisno prema manje ili više složenim izrazima, pošto je polje u zubima jedinstveno.

2 RASPODJELA MAGNETSKOG POLJA U ZUBIMA

Pri analitičkom proračunu kao prvo pojednostavljenje uzima se homogena raspodjela permeabilnosti i vodljivosti u željezu paketa limova, a proračun se zatim započinje od jednostavnih oblika zuba (pravokutni oblik), radi izbjegavanja matematičkih teškoća koje se javljaju pri proračunu polja i gubitaka u zubima složenijih oblika.

Polje u zubu može se odrediti iz Laplaceove jednadžbe za skalarni magnetski potencijal:

For that reason, the analytic calculation of eddy current losses in the teeth of the induction motor is assessed in this work only by virtue of comparison with the numerical results obtained by the finite element method.

The work derives expressions for the analytic calculation of losses. However, as in the available literature [1], [2] and [3], without proof of the admissibility thereof, surface and pulsation losses are calculated independently, it is necessary to prove that surface and pulsation losses may be calculated independently according to more or less complex expressions because the field in the teeth is unique.

2 DISTRIBUTION OF THE MAGNETIC FIELD IN THE TEETH

At analytical calculation, homogenous distribution of permeability and conductivity in the sheet metal packages is taken as the first simplification, and the calculation then starts from simple teeth forms (rectangular form) for the purpose of avoiding mathematical difficulties which arise at calculation of fields and losses in the complex-form teeth.

The field in the teeth can be determined from the Laplace equation for the scalar magnetic potential:

$$\Delta\varphi = \frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = 0, \tag{1}$$

gdje je:

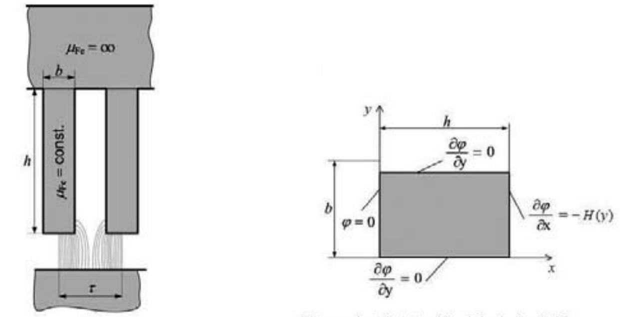
φ – skalarni magnetski potencijal,
x, y – komponente (vektora).

Na slici 1a) je prikazan zub i stvarna raspodjela polja u zračnom rasporu za jedan utorski korak, dok je na slici 1b) prikazan pravokutni zub i koordinatni sustav, te su naznačeni rubni uvjeti. Laplaceova jednadžba za skalarni magnetski potencijal, u ovom se slučaju, može riješiti separacijom varijabli, tako da se pretpostavi da je rješenje produkt funkcija samo jedne varijable.

where it is as follows:

φ – scalar magnetic potential,
x, y –(vector) components.

Figure 1a) shows the tooth and the actual distribution of the fields in the air gap for one slot step, while Figure 1b) shows the rectangular tooth and the coordinate system, as well as an indication of boundary conditions. The Laplace equation for the scalar magnetic potential, in this case, may be solved by a separation of the variables so as to assume that the solution is a product of functions of only one variable.



a) stvarno polje u utorskom koraku /
actual field in the slot step

b) pravokutni statorski zub i rubni uvjeti /
rectangular stator tooth and boundary conditions

Slika 1 — Polje u zračnom rasporu i koordinatni sustavi
Figure 1 — The field in the air gap and the coordinate systems

Daljnji postupak određivanja vektora jakosti magnetskog polja kao rješenja Laplaceove jednadžbe za skalarni magnetski potencijal detaljno je opisan u [5].

Iz definicije skalarnog magnetskog potencijala prema izrazu (2), dobiva se dvodimenzionalni vektor jakosti magnetskog polja (3), koji ima samo dvije komponente, jer je početna pretpostavka da se zanemaruje čeoni prostor stroja u proračunu gubitaka, što je u skladu sa 2D numeričkim proračunom magnetskog polja asinkronog motora korištenjem metode konačnih elemenata:

Further procedure for the determination of the magnetic feld strength vector as a solution of the Laplace equation for the scalar magnetic potential is described in detail in [5].

The definition of the scalar magnetic potential according to the expression (2), a two-dimensional vector of magnetic field strength (3) is derived and has only two components because the initial assumption is that the frontal machine area is disregarded in the calculation of losses, which is in accordance with the 2D numerical calculation of the induction motor magnetic field by using the finite element method:

$$\boldsymbol{H} = -\nabla\varphi \tag{2}$$

$$\boldsymbol{H} = \boldsymbol{H}_x + \boldsymbol{H}_y = \mathbf{i}\cdot H_x + \mathbf{j}\cdot H_y \ . \tag{3}$$

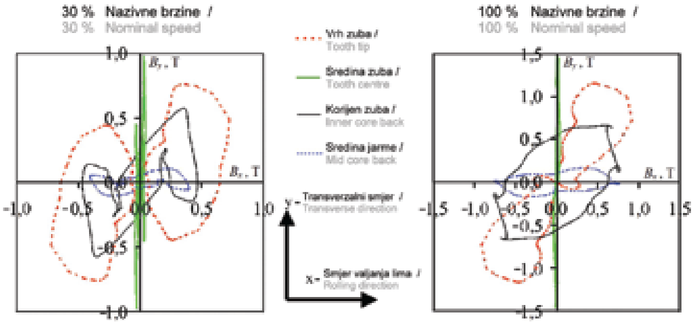
Poznavanje struja statorskog namota i rotorskog kaveza omogućava da se metodom konačnih elemenata proračuna raspodjela magnetskog polja u presjeku stroja. Ako se izračun načini za neopterećen motor, dovoljno je poznavati samo struju statorskog namota, na osnovi koje se onda mogu izračunati struje rotorskog kaveza. U slučaju opterećenog motora napajanog iz sinusoidalnog izvora sa skošenim rotorskim kavezom, skošenje se promatra odvojeno za proračun korištenjem metode konačnih elemenata, tj. rotor se segmentira na dijelove s neskošenim rotorom, koji su međusobno prostorno pomaknuti, te se kompletan rotorski kavez čini skošen [6].

Izrazi za gubitke u željezu paketa limova neopterećenog motora korištenjem 3D modela magnetskog polja su izvedeni u [7]. Postupak određivanja gubitaka u željezu paketa limova statora i rotora asinkronog motora započinje rastavljanjem neodređenog oblika promjene vektora magnetske indukcije, korištenjem Fourierovog reda, na niz

Knowing the stator winding and rotor cage currents enables the calculation of the distribution of the magnetic field in the machine intersection by virtue of the finite element method. If the calculation is made for an unloaded motor, it suffices to know only the stator winding current based on which the rotor cage currents can be calculated. In the case of a loaded motor fed from the sinusoidal source with a skew rotor cage, the skewing is observed separately for the calculation by using the finite element method, that is, the rotor is divided in segments with non-skewed rotors, which are mutually spatially shifted, and so it all looks like a skew squirrel cage rotor [6].

Expressions for losses in the iron sheet metal package of the unloaded motor by using the 3D magnetic feld model are derived in [7]. The procedure for the determination of the induction motor stator and rotor iron sheet metal package starts with the dissection of the undetermined change eliptičkih harmonika vektora magnetske indukcije. Za svaki je harmonik određena komponenta magnetskog toka u smjeru glavne osi, poprečne osi, te je definiran omjer eliptičnosti. Ukupni su gubici zatim definirani kao zbroj gubitaka histereze (rotacijskih i izmjeničnih gubitaka), ukupnih gubitaka vrtložnih struja i dodatnih gubitaka. Takva složena definicija gubitaka zahtijeva vrlo složene postupke određivanja krivulje magnetiziranja lima u rotacijskom magnetskom polju što nije praktično u inženjerskoj praksi (slika 2).

type of the magnetic induction vector, by using the Fourier series, into a series of elliptic harmonics of the magnetic induction vectors. A magnetic flux component is determined for each harmonic in the direction of the main axis, the transverse axis, and the elliptic ratio is defined as well. Total losses are then defined as the aggregate of hysteresis losses (rotational and alternate losses), total eddy current losses and additional losses. Such a complex definition of losses demands very complex procedures for the determination of the sheet magnetizing curve in the rotational magnetic field which is not convenient in engineering practice (Figure 2).



Slika 2 — Prikaz deformiranog 2D valnog oblika raspodjele magnetske indukcije zbog slabljenja polja uzduž statorskog zuba pri promjeni brzine motora

Figure 2 — Overview of the deformed 2D waveform of the distribution of the magnetic induction due to fields weakening along the stator tooth at change in motor speed

3 ANALITIČKI MODEL IZRAČUNA GUBITAKA U ZUBIMA

Za određivanje gubitaka u zubima paketa limova potrebno je prvo odrediti trenutačni iznos gubitaka u jednom zubu jednog lima:

3 ANALYTICAL MODEL FOR THE CALCULATION OF LOSSES IN THE TEETH

For the determination of the losses in the sheet package teeth, it is first of all necessary to determine the momentary amount of losses in one tooth of one sheet:

$$p_{\mathrm{gz}\mu\mathrm{l}}(t)=\frac{1}{\kappa_{\mathrm{Fe}}}\iiint_{V_{\mathrm{zl}}}|\boldsymbol{J}(x,y,z,t)|^2\,\mathrm{d}V \qquad (4)$$

gdje je:

p – trenutačni iznos snage, W,
$\boldsymbol{J}$ – vektor gustoće struje, $\mathrm{A/m^2}$,
κ – vodljivost, S/m,
V – volumen, $\mathrm{m^3}$,
t – vrijeme, s,
x,y,z – koordinate, m,
Fe – željezo,
g – gubici,
z – zub,
l – lim,
μ – oznaka harmonika.

where it is as follows:

p – momentary amount of power, W,
$\boldsymbol{J}$ – current density vector, $\mathrm{A/m^2}$,
κ – conductivity, S/m,
V – volume, $\mathrm{m^3}$,
t – time, s,
x,y,z – coordinates, m,
Fe – iron,
g – losses,
z – tooth,
l – metal sheet,
μ – harmonics symbol.

Ako se pretpostavi da je lim u *x*, *y* ravnini (debljina lima je u smjeru *z* osi), uz zanemarivanje utjecaja vrtložnih struja na raspodjelu indukcije u zubu [8], može se pretpostaviti da se *y* komponenta gustoće struje linearno mijenja s koordinatom *z* te naknadno uzeti u obzir efekt potiskivanja toka u limu. Također, može se pretpostaviti da je vektor $\boldsymbol{J}_y$ proporcionalan s $\boldsymbol{H}_x$, ali vremenski pomaknut za 90 °. Iz toga slijedi da za trenutačnu vrijednost gubitaka u jednom zubu jednog lima vrijedi izraz (5), a srednja vrijednost tih gubitaka prikazana je izrazom (6):

Assuming that the metal sheet is in the *x*, *y* plain (sheet thickness is in the direction of the *z* axis), disregarding the impact of eddy currents on the distribution of the induction in the tooth [8], it can be assumed that the current density component *y* linearly changes with the *z* coordinate and the effect of flow suppression in the sheet metal can be taken into consideration subsequently. Moreover, it can be assumed that the $\boldsymbol{J}_y$ vector is proportionate to $\boldsymbol{H}_x$, but temporally shifted by 90 °. From this it ensues that for the momentary value of losses in one tooth of one sheet metal, the expression (5) applies and the average value of those losses is depicted by the expression (6):

$$p_{\mathrm{gz}\mu\mathrm{l}}(t)=\frac{1}{\kappa_{\mathrm{Fe}}}\iiint\limits_{V_{\mathrm{zl}}}\left|\boldsymbol{J}_x+\boldsymbol{J}_y\right|^2\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\ , \tag{5}$$

$$P_{\mathrm{gz}\mu\mathrm{l}}=\frac{\omega_\mu}{2\pi}\int\limits_0^{\frac{2\pi}{\omega_\mu}}p_{\mathrm{gz}\mu\mathrm{l}}\,\mathrm{d}t=\frac{1}{\kappa_{\mathrm{Fe}}}\int\limits_{\frac{-\delta}{2}}^{\frac{\delta}{2}}\int\limits_0^b\int\limits_0^h\frac{\omega_\mu}{2\pi}\int\limits_0^{\frac{2\pi}{\omega_\mu}}\left(J_x^2+J_y^2\right)\mathrm{d}t\ \mathrm{d}x\mathrm{d}y\mathrm{d}z\ , \tag{6}$$

gdje je:

P – srednja vrijednost trenutne vrijednosti snage, W,
b – širina zuba, m,
h – visina zuba, m,
δ – debljina lima, m
ω – kružna frekvencija, rad/s.

where it is as follows:

P – average value of the momentary power value, W,
b – tooth width, m,
h – tooth height, m,
δ – metal sheet thickness, m,
ω – circular frequency, rad/s.

Integriranjem prema (6) dobiva se konačan izraz za gubitke u jednom zubu jednog lima (7), gdje je faktor utjecaja otvora utora definiran izrazom (8), a koeficijent α_μ je definiran izrazom (9):

By integration according to (6), the final expression is gained for the losses in one tooth of one sheet (7), where the factor of the impact of the slot opening is defined by the expression (8), and the coefficient α_μ is defined by the expression (9):

$$P_{\mathrm{gz}\mu\mathrm{l}}=\frac{\delta^3}{24\kappa_{\mathrm{Fe}}}\left(\frac{\kappa_{\mathrm{Fe}}\,B_\mu\ \omega_\mu}{k_{\mathrm{Fe}}}\right)^2\left\{h\cdot b\left[\frac{\sin\left(\alpha_\mu\frac{\pi}{2}\right)}{\alpha_\mu\frac{\pi}{2}}\right]^2+\frac{R\cdot b}{\mu}K(\mu)\right\}\ , \tag{7}$$

$$K(\mu)=\frac{8\alpha_\mu^3}{\pi^2}\left[\sum_{n=2,4,\ldots}^{\infty}\frac{\sin^2\left(\alpha_\mu\frac{\pi}{2}\right)}{n\left(n^2-\alpha_\mu^2\right)^2}\mathrm{th}\left(n\pi\frac{h}{b}\right)+\sum_{n=1,3,\ldots}^{\infty}\frac{\cos^2\left(\alpha_\mu\frac{\pi}{2}\right)}{n\left(n^2-\alpha_\mu^2\right)^2}\mathrm{th}\left(n\pi\frac{h}{b}\right)\right]\ , \tag{8}$$

$$\alpha_\mu=\mu\frac{b}{R\pi}\ , \tag{9}$$

gdje je:

B – amplituda indukcije, T,

where it is as follows:

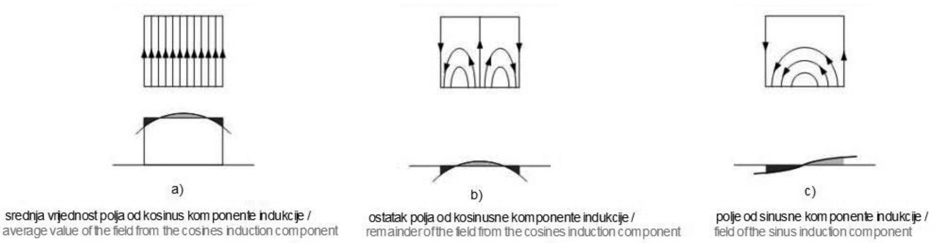
B – induction amplitude, T,

k_{Fe} – faktor punjenja željeza,
R – polumjer provrta statorskog paketa limova, m,
K – faktor utjecaja otvora utora na površinske gubitke,
n – cijeli broj (redni broj harmonika).

Prvi član u vitičastoj zagradi u (7) potječe od homogenog polja prikazanog na slici 3a) koje je polazište je za proračun pulzacijskih gubitaka. Drugi član u vitičastoj zagradi u (7) potječe od polja prikazanog na slikama 3b) i 3c), koja su polazište za proračun površinskih gubitaka prema [2], [5] i [8].

k_{Fe} – iron filling factor,
R – radius of the bore of the stator sheet metal package, m,
K – factor of the slot opening impact on surface losses,
n – full number (harmonics ordinal number).

The first term in convolute brackets in (7) originates from the homogenous field shown in Figure 3a) which is the starting point for the pulsation losses calculation. The second term in convolute brackets in (7) originates from the field shown in Figures 3a) and 3b) which are the starting point for the surface losses calculation according to [2], [5] and [8].



Slika 3 — Komponente magnetskog polja u zubu
Figure 3 — The components of the magnetic field in the tooth

Ukupni gubici u zubima prema izrazu (10) dobiveni su množenjem srednje vrijednosti gubitaka u jednom zubu jednog lima s brojem zubi i omjerom duljine željeza prema debljini lima, pri čemu su pulzacijski gubici u zubima definirani izrazom (11), a površinski gubici izrazom (12):

Total losses in the teeth according to the expression (10) are obtained by multiplying the average value of losses in one tooth of one metal sheet with the number of teeth and iron length ratio according to sheet thickness, whereat the pulsation losses in the teeth are defined by the expression (11) and surface losses by the expression (12):

$$P_{\mathrm{gz}\mu} = Q\frac{l_{\mathrm{u}}}{\delta}P_{\mathrm{gz}\mu\mathrm{l}} = P_{\mathrm{gz}\mu\mathrm{pul}} + P_{\mathrm{gz}\mu\mathrm{pov}} \quad , \tag{10}$$

$$P_{\mathrm{gz}\mu\mathrm{pul}} = \frac{\kappa_{\mathrm{Fe}}}{24\,k_{\mathrm{Fe}}}\left(\omega_\mu \delta\right)^2 \left[B_\mu \frac{\sin\left(\alpha_\mu \frac{\pi}{2}\right)}{\alpha_\mu \frac{\pi}{2}}\right]^2 Q\,l_{\mathrm{e}}\,h\,b \ , \tag{11}$$

$$P_{\mathrm{gz}\mu\mathrm{pov}} = \frac{\kappa_{\mathrm{Fe}}\,k_{\mathrm{C}}^2}{24\,k_{\mathrm{Fe}}}\left(\omega_\mu B_\mu \delta\right)^2 2\pi\, R_{\mathrm{e}} l\, \frac{b}{\tau}\frac{R}{\mu}K(\mu) \ , \tag{12}$$

gdje je:

Q – broj zuba,
l – duljina paketa limova, m,
τ – utorski korak, m,
pov – površinski,
pul – pulzacijski,
u – ukupna vrijednost,
e – efektivna (idealna) vrijednost.

where it is as follows:

Q – number of teeth,
l – metal sheet package length, m,
τ – slot step, m,
pov – surface,
pul – pulsation,
u – total value,
e – effective (ideal) value.

Iz izvoda polja i gubitaka proizlazi da se za pravokutne zube, uz navedene pretpostavke $\mu_{\mathrm{Fe}} = \mathrm{konst.}$ i $k_{\mathrm{Fe}} = \mathrm{konst.}$, pulzacijski i površinski gubici vrtložnih struja mogu računati odvojeno.

Ta se spoznaja koristi i pri proračunima gubitaka u zubima složenijih oblika. Za određivanje konačnih izraza za gubitke potrebno je prvo načiniti korekcije, kojima se u obzir uzima stvarna raspodjela polja prema slici 1a). Izraz za proračun pulzacijskih gubitaka u pravokutnim zubima tada vrijedi izraz (13), gdje je k_{C} Carterov faktor za stator ili rotor, ovisno gdje se računaju gubici, a nadomjesni volumen zubi definiran je izrazom (14). Zbog vrlo složenog polja uz zračni raspor, za pravokutne zube i za složenije oblike zuba najbolje je površinske gubitke računati pojednostavljeno izrazom (15):

From the extraction of the fields and losses, the derivation is that for rectangular teeth, with the mentioned assumptions $\mu_{\mathrm{Fe}} = \mathrm{konst.}$ and $k_{\mathrm{Fe}} = \mathrm{konst.}$, pulsation and surface eddy current losses can be calculated separately.

That cognition is also used at calculation of losses in complex-form teeth. For the determination of final expressions for the losses, the first thing to do is to make corrections which take into consideration the actual distribution of the field according to Figure 1a). Then the expression (13) applies to the calculation of pulsation losses in rectangular teeth, and there k_{C} is the Carter factor for the stator or the rotor, depending on where the losses are calculated, and the equivalent number of teeth is defined by the expression (14). Because of the very complex field along the air gap, for rectangular teeth and more complex teeth forms, it is best to calculate surface losses in a simplified manner by the expression (15).

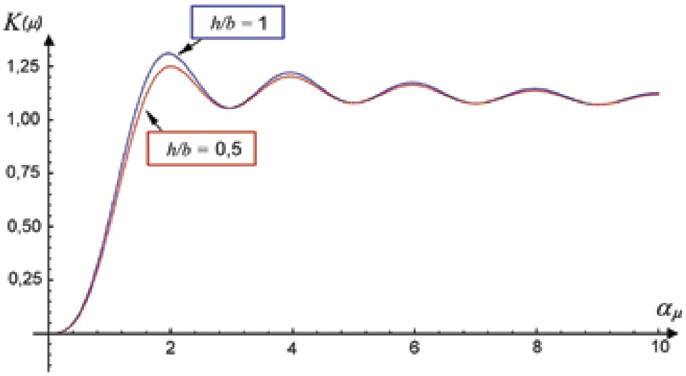
$$P_{\mathrm{gz}\mu\mathrm{pul}} = \frac{\kappa_{\mathrm{Fe}}}{24\, k_{\mathrm{Fe}}} \left(\omega_\mu \delta\right)^2 \left[k_{\mathrm{C}} B_\mu \frac{\sin\left(\frac{\tau}{k_{\mathrm{C}}\, b} \alpha_\mu \frac{\pi}{2}\right)}{\alpha_\mu \frac{\pi}{2}} \right]^2 V_{\mathrm{e}} \, , \tag{13}$$

$$V_{\mathrm{e}} = Q\, l_{\mathrm{e}}\, h\, b \, , \tag{14}$$

$$P_{\mathrm{gz}\mu\mathrm{pov}} = \frac{\kappa_{\mathrm{Fe}}\, k_{\mathrm{C}}^2}{24\, k_{\mathrm{Fe}}} \left(\omega_\mu B_\mu \delta\right)^2 2\pi\, R\, l_{\mathrm{e}} \frac{b}{\tau} \frac{R}{\mu} K(\mu) \, . \tag{15}$$

Faktor utjecaja otvora utora $K(\mu)$ prema (8) prikazan je na slici 4, općenitiji je od odgovarajućeg faktora u [2], koji je identičan izrazu koji se dobiva iz (8) ako se u uzme da je $\mathrm{th}(n\pi h/b) = 1$, što je u pravilu dopušteno zbog toga što omjer $h/b > 1$ vrijedi za obrađivanu grupu motora.

The slot opening impact factor $K(\mu)$ according to (8) is shown in Figure 4; it is more general than the equivalent factor in [2], which in turn is identical to the expression obtained from (8) if $\mathrm{th}(n\pi h/b) = 1$ is implied, which is generally allowed because the ratio $h/b > 1$ applies to the studied motor group.



Slika 4 — Faktor utjecaja otvora utora na površinske gubitke
Figure 4 — Factor of slot opening impact on surface losses

Formule za proračun pulzacijskih i površinskih gubitaka vrtložnih struja (13) i (15) potrebno je korigirati utjecajem potiskivanja toka u limovima, utjecajem prigušenja toka u zubima, te utjecajem obrade lima i paketa limova. Da bi se dobili ukupni gubici u zubima treba dodati pojednostavljeno određene gubitke histereze [1] i [8].

Pri proračunu pulzacijskih gubitaka za korekciju utjecaja potiskivanja toka u limovima [3], treba za korigiranu širinu zuba [8] odrediti indukciju, a iz nje odgovarajuću relativnu permeabilnost. Korigirane vrijednosti permeabilnosti za proračun gubitaka magnetiziranja određuju se iz krivulje prvog magnetiziranja, za proračun dodatnih gubitaka uzrokovanih višim harmonicima polja u zračnom rasporu treba uzeti inkrementalnu ili diferencijalnu permeabilnost [3], dok je pri proračunima površinskih gubitaka za određivanje permeabilnosti mjerodavna širina zuba uz zračni raspor (kruna zuba).

Faktor prigušenja toka u zubima koristi se samo pri proračunu pulzacijskih gubitaka, te je za gubitke u zubima neskošenih rotora određen u [3]. Najteže je odrediti faktore korekcije zbog obrade lima i paketa limova, jer oni osim o svojstvima lima ovise o rezu lima i tehnologiji izrade paketa. Za određivanje tih faktora potrebno je raspolagati s mjerenjima utjecaja vrste obrade (tokarenje, brušenje) na probama lima [4], te poznavati tehnologiju izrade paketa limova. Na kraju je ipak potrebno, unatrag, iz mjerenja gubitaka (osnovnih i dodatnih) i proračuna po teorijskim formulama za gubitke, korigirati faktore određene iz mjerenja na probama lima.

4 NUMERIČKI POSTUPAK ODREĐIVANJA GUBITAKA U ZUBIMA

Za numerički proračun gubitaka u zubima statora i rotora asinkronog kaveznog motora korištena je metoda konačnih elemenata i iterativni proračun. Tako dobiveni rezultati uspoređeni su s rezultatima analitičkog proračuna gubitaka kako bi se odredio utjecaj pojednostavljenja u analitičkom modelu za određivanje gubitaka u zubima. Numerički proračun polja metodom konačnih elemenata temelji se na Maxwellovim jednadžbama, koje sačinjavaju temeljne zakone kojima se podvrgavaju sve električne i magnetske pojave. Iako se Maxwellove jednadžbe primjenjuju na cijeli prostor, praktični problemi su konačnih dimenzija, pa su rješenja Maxwellovih jednadžbi unutar tih područja povezana s

Formulas for the calculation of pulsation and surface eddy current losses (13) and (15) need to be corrected by the impact of the suppression of fluxes in the metal sheets, the impact of flux losses in the teeth and the impact of metal sheet and metal sheet package processing. In order to get total losses in the teeth, the hysteresis losses determined in a simplified manner need to be added [1] and [8].

At calculation of pulsation losses for the correction of impacts of flux suppressions in the sheets [3], for the corrected teeth width [8], induction needs to be defined and from this, the adequate relative permeability. Corrected permeability values for magnetizing loss calculation are determined from the first magnetizing curve; the calculation of additional losses caused by higher harmonics of fields in the air gap require the incremental or differential permeability, while teeth width along the air gap (tooth crown) is relevant for the calculation of surface losses for the determination of permeability.

The teeth flux attenuation factor is used only at calculation of pulsation losses and for the losses in the teeth of non-skewed rotors, it is determined in [3]. The hardest part is to determine the correction factors due to sheet and sheet packages processing because they depend not only on the sheet cutting but also on the package fabrication technology. The determination of those factors requires the availability of measurements of the impacts of types of processing (turning, grinding) on sheet tests [4], and knowing the sheet package fabrication technology. In the end, it is necessary, nevertheless, to use the measurements of the losses (fundamental and additional) and calculations according to theoretical loss formulas to make backward corrections of factors determined from the measurements on sheet tests.

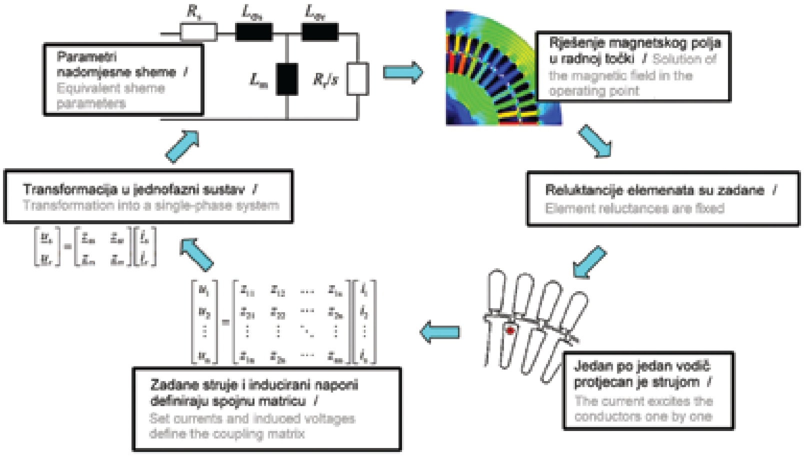
4 NUMERICAL PROCEDURE FOR THE DETERMINATION OF THE LOSSES IN THE TEETH

The finite element method and the iterative calculation were used for the numerical calculation of the losses in the teeth of the stator and rotor of the induction squirrel cage motor. The results gained in such a manner are compared with the results of the analytical calculation of losses in order to determine the impact of the simplification in the analytical model for the determination of losses in the teeth. The numerical calculation of fields by virtue of the finite element method is based on Maxwell's equations which constitute the basic laws to which all electrical and magnetic occurrences are subjected. Although Maxwell's equations apply to the entire area, practical problems are of final dimensions and so the solutions of Maxwell's equations within those areas are okolnim prostorom korištenjem rubnih uvjeta i početnih vrijednosti.

Postupak definiranja mreže konačnih elemenata dijeli se na odvojeno mreženje dva prostora. Prvi je prostor od središta osovine do polovice zračnog raspora (rotorski prostor), a drugi od sredine zračnog raspora prema van (statorski prostor). Pri tome se dodirna kontura oba prostora dijeli na jednak broj dijelova (inkremenata), koji mora biti višekratnik broja utora statora i rotora. Iterativni postupak proračuna odnosi se na zakretanje rotorskog prostora za inkrement, te strujni izračun nadomjesne sheme asinkronog motora čiji parametri se računaju iz proračuna polja metodom konačnih elemenata (slika 5). Rezultat strujnog proračuna je raspodjela struja koja je potrebna za sljedeći korak proračuna polja metodom konačnih elemenata. Ovisno o brzini rotora u postupku proračuna (kratki spoj, zalet, nazivna radna točka, prazni hod) mijenja se trajanje zakreta rotorskog prostora za inkrement, što ulazi u proračun parametara nadomjesne sheme za strujni proračun.

connected to the surrounding area by using boundary conditions and initial values.

The procedure for the definition of the finite element network is divided into separate networking of two spaces. The first area is from the middle of the axis to the half of the air gap (rotor space) and the other is from the middle of the air gap outwards (stator space). Thereat, the boundary contour of both spaces is divided into the same number of parts (increments) which must be the multiple of the number of stator and rotor slots. The iterative calculation procedure relates to the rotation of the rotor space for the increment and the current calculation of the induction motor equivalent scheme with parameters that are calculated from the calculation of the field by virtue of the finite element method (Figure 5). The result of the current calculation is the distribution of currents necessary for the next step of the calculation by virtue of the finite element method. Depending on the rotor speed in the calculation process (short circuit, start up, nominal operating point, idle running), the duration of the rotation of the rotor space for the increment changes, and this is put into the calculation of the parameters of the equivalent scheme for the current calculation.



Slika 5 — Iterativni postupak za numerički proračun električnih parametara asinkronog motora na osnovi izračuna magnetskog polja metodom konačnih elemenata

Figure 5 — Iterative procedure for the numerical calculation of the asynchronous motor parameters based on the calculation of magnetic fields using the finite element method

5 VREDNOVANJE ANALITIČKOG MODELA IZRAČUNA GUBITAKA PRAZNOG HODA USPOREDBOM S REZULTATIMA MJERENJA

Za analizu modela proračuna gubitaka praznog hoda i njegovu usporedbu s mjerenjima, odabrana su dva asinkrona kavezna motora iz proizvodnog

5 VALUATION OF THE ANALYTICAL MODEL FOR IDLE RUNNING LOSS CALCULATION BY COMPARISON WITH THE MEASUREMENTS RESULTS

For the analysis of the model for the calculation of the idle running losses and its comparison with the measurements, two induction squirrel cage programa poduzeća KONČAR. Podaci tih motora prikazani su u tablici 1.

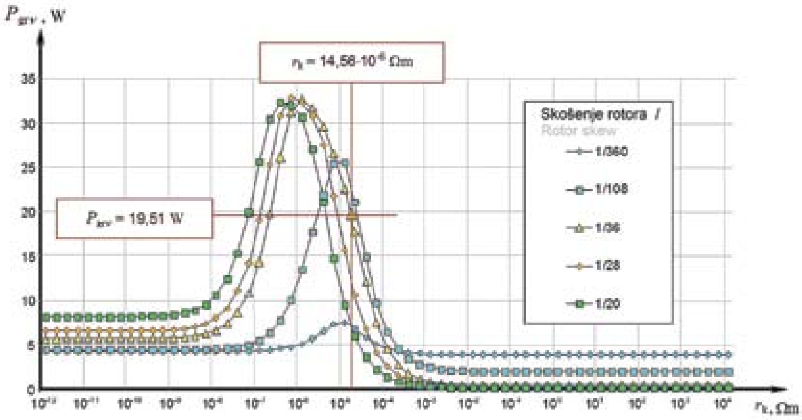
motors have been selected from the KONČAR company programme. Data on those motors are shown in Table 1.

Tablica 1 – Podaci motora na kojima su mjereni gubici praznog hoda
Table 1 – Data on motors on which idle running losses were measured

	MOTOR 1	MOTOR 2
Nazivna snaga / Nominal power, kV	7,5	11
Nazivni napon / Nominal voltage, V	380	380
Nazivna struja / Nominal current, A	15,2	22,7
Nazivni brzina vrtnje / Nominal rotation speed, mm^{-1}	1450	965
Faktor snage / Power factor	0,86	0,84
Korisnost / Efficiency	0,87	0,88
Broj pari polova / Number of pole pairs	2	3
Broj utora statora / Number of stator slots	36	54
Broj utora rotora / Number of rotor slots	28	40
Skošenje štapova kaveza rotora / Rotor cage bar skewing	1/36	1/54

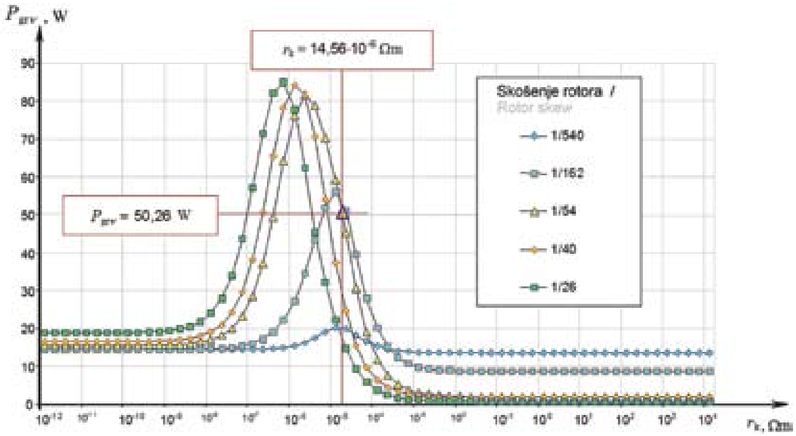
Postupak analitičkog proračuna počinje od proračuna struje magnetiziranja, a zatim se preko analitički određene vrijednosti nadomjesnog otpora željeza statorskog paketa limova dobiva vrijednost osnovnih gubitaka u statorskom paketu limova. Pri proračunu dodatnih gubitaka pored primarne u proračun je uzeta i sekundarna reakcija armature [8]. Primarna reakcija armature uključuje proračun gubitaka poprečnih struja (P_{grv}). Konačne vrijednosti kontaktnih otpora između štapova kaveza i paketa limova rotora dovode do povećanja dodatnih gubitaka. Izmjerena vrijednost kontaktnih otpora [8] za oba motora je $r_k = 14{,}56 \cdot 10^{-6}\,\Omega\text{m}$. Ovisnost gubitaka poprečnih struja o vrijednostima kontaktnog otpora uz različite vrijednosti skošenja za oba motora prikazana je dijagramima na slikama 6 i 7.

The analytical calculation procedure starts with the calculation of the magnetizing current and then, through the analytically determined value of the equivalent resistance of the stator metal sheet package the amount of the basic losses in the stator sheet metal package is obtained. At calculation of additional losses, besides the primary reaction, the secondary armature reaction is also taken into the calculation [8]. The primary armature reaction includes the calculation of the transverse current losses (P_{grv}). Final values of contact resistances between the squirrel cage bars and the rotor sheet metal packages give rise to an increase of additional losses. The measured value of contact resistances [8] for both motors is $r_k = 14{,}56 \cdot 10^{-6}\,\Omega\text{m}$. The dependency of losses of transverse current on the values of the contact resistance with different skew values for both motors is shown in diagrams in Figures 6 and 7.



Slika 6 — Ovisnost gubitaka poprečnih struja o vrijednostima kontaktnog otpora uz različite vrijednosti skošenja rotora za motor 1

Figure 6 — The dependency of transverse current losses on the values of the contact resistance with different values of the rotor skew for motor 1



Slika 7 — Ovisnost gubitaka poprečnih struja o vrijednostima kontaktnog otpora uz različite vrijednosti skošenja rotora za motor 2

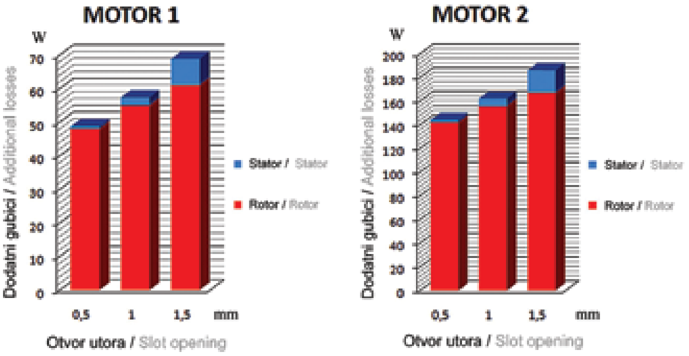
Figure 7 — The dependency of transverse current losses on the values of the contact resistance with different values of the rotor skew for motor 2

Uz gubitke poprečnih struja u proračunu su još uzeti u obzir i pulzacijski i površinski gubici. Pri proračunu dodatnih gubitaka u statorskom namotu proračun indukcija i parametara statorskog namota različit je za pojedine harmonike (temeljni harmonik, harmonici čiji je broj pari polova višekratnik broja tri i ostali harmonici).

Iz prethodnih se poglavlja vidi da dodatni gubici, pored ostalog, ovise i o širini otvora utora na rotoru. Na slici 8 prikazana je ovisnost gubitaka o širini otvora utora, gdje je vidljivo da povećanje širine otvora utora dovodi do povećanja gubitaka zbog poprečnih struja, tj. do povećanja dodatnih gubitaka u rotoru. Također, uz povećanje gubitaka zbog poprečnih struja dolazi i do povećanja pulzacijskih i površinskih gubitaka i u rotoru i u statoru, tj. do povećanja dodatnih gubitaka u statoru.

Besides the transverse current losses the calculation also took into consideration the pulsation and surface losses. At calculation of additional losses in the stator winding, the calculation of the inductions and parameters of the stator winding is different for certain harmonics (basic harmonic, harmonics with the number of pole pairs being the multiple of number three and other harmonics).

It is evident from the previous chapters that additional losses, inter alia, also depend on the rotor slot opening width. Figure 8 shows the dependency of losses on the slot opening width, where it is evident that the increase of the slot opening width brings about an increase of losses due to the transverse currents, that is, to the increase of additional rotor losses. Moreover, with the increase of losses due to transverse currents, an increase of pulsation and surface losses also occurs in the rotor and in the stator, that is, an increase of additional losses in the stator.



Slika 8 — Prikaz raspodjele dodatnih gubitaka u rotoru i statoru motora s obzirom na promjenu širine otvora utora

Figure 8 — Overview of the distribution of the losses in the motor rotor and stator considering the change of the slot opening width

Zbrajanjem dodatnih gubitaka u rotoru i statoru dobivaju se dodatni gubici u praznom hodu. Usporedba rezultata analitičkog proračuna i izmjerenih vrijednosti za oba motora dana je u tablici 2.

By adding up additional losses in the rotor and the stator, additional idle running losses are gained. Comparison of the results of the analytical calculation and the measured values for both motors are given in Table 2.

Tablica 2 – Rezultati analitičkog proračuna gubitaka praznog hoda i njihova usporedba s mjerenim rezultatima
Table 2 – The results of the analytical calculation of the idle running losses and their comparison with the measured results

Veličina / Size	MOTOR 1			MOTOR 2		
	Izračunate vrijednosti / Calculated values, W	Izmjerene vrijednosti / Measured values, W	Relativna pogreška / Relative error, %	Izračunate vrijednosti / Calculated values, W	Izmjerene vrijednosti / Measured values, W	Relativna pogreška / Relative error, %
Osnovni gubici u željezu / Basic losses in the iron P_{Fe10}	124,3	138	-9,9	262,6	212	23,6
Dodatni gubici / Additional losses P_{dod0}	57,5	58	-0,9	162,0	132	22,7
Ukupni gubici praznog hoda / Total idle running losses P_0	317,8	332	-4,3	570,6	503,4	13,3

Razlika između proračuna i mjerenja u prvom je redu uvjetovana ispravnošću ulaznih podataka motora s kojima se ulazi u proračun. To se prvenstveno odnosi na kvalitetu lima i na stvarnu veličinu zračnog raspora, što bitno utječe na iznos gubitaka praznog hoda. Pritom pogreška u veličini zračnog raspora u iznosu od desetinke milimetra može dovesti do promjene konačne vrijednosti dodatnih gubitaka u iznosu od desetak wata. Razmatrani proračun gubitaka u praznom hodu ukazuje da:

- dodatni gubici mogu biti znatan dio ukupnih gubitaka praznog hoda,
- pretežiti dio gubitaka može nastati u statorskom i rotorskom paketu limova.

Dodatni gubici koje uzrokuju raspored namota u utorima i otvori utora, utječu na dodatno zagrijavanje motora, te smanjuju korisnost.

6 VREDNOVANJE ANALITIČKOG MODELA IZRAČUNA GUBITAKA VRTLOŽNIH STRUJA USPOREDBOM S REZULTATIMA NUMERIČKOG PRORAČUNA

Za vrednovanje analitičkog modela proračuna gubitaka vrtložnih struja u zubima asinkronog motora s numeričkim rezultatima dobivenih metodom konačnih elemenata odabran je šesteropolni asinkroni kavezni motor (KONČAR): 30 kW, 380 V, 973 o/min.

The difference between the calculation and the measurement is conditioned in the first place by the correctness of those input data on the motor which enter the calculation. This is primarily related to the sheet quality and the actual air gap size which significantly affects the amount of idle running losses. Thereat the error in the size of the air gap in the amount of one tenth of a millimetre may bring about a change of the final value of additional losses in the amount of some ten watts. The studied calculation of idle running losses points to the following:

- additional losses may be a significant part of the total idle running losses,
- most of the losses may occur in the stator and rotor metal sheet packages.

Additional losses caused by the spacing of the windings in the slots and the slot openings affect the additional motor heating and decrease the efficiency.

6 VALUATION OF THE ANALYTICAL MODEL FOR EDDY CURRENT LOSS CALCULATION BY COMPARISON WITH THE RESULTS OF THE NUMERICAL CALCULATION

A six-pole induction squirrel cage motor (KONČAR) was selected for the valuation of the analytical model for the calculation of eddy current losses in the induction motor teeth with the numerical result obtained by virtue of the finite element method: 30 kW, 380 V, 973 o/min.

Pored osnovnih gubitaka u statorskom paketu limova potrebno je odrediti i dodatne gubitke u rotorskom kavezu i statorskom namotu (primarna i sekundarna reakcija armature [8]), te dodatne gubitke u rotorskom i statorskom paketu limova uzrokovanih harmonicima protjecanja statorskog namota i kaveza. Pri određivanju iznosa harmonika indukcije potrebno je uzeti u obzir nazubljenje statorskog i rotorskog paketa limova. U proračunu gubitaka u željezu za faktore obrade lima i paketa limova uzete su sljedeće vrijednosti:

- 1,6 – za proračun osnovnih gubitaka u statorskom paketu limova,
- 2,2 – za proračun pulzacijskih dodatnih gubitaka,
- 2,2 – za proračun površinskih gubitaka na statoru i
- 3,8 – za proračun površinskih gubitaka na rotoru [8].

Iz definicije protjecanja za m_s fazni namot, slijedi da u asinkronom motoru pored osnovnog harmonika nastaje i sustav viših harmonika koji se dijeli na direktni i inverzni sustav harmonika [1] i [9], a koji se može definirati izrazom:

Besides the basic losses in the stator sheet metal package, it is also necessary to determine additional losses in the rotor cage and the stator winding (primary and secondary armature reaction [8]), and additional losses in the rotor and stator metal sheet package caused by the magnetic flux harmonics of the stator winding and the squirrel cage. At determination of the amounts of the induction harmonics, it is necessary to take into consideration the serration of the stator and rotor sheet metal package as well. The following values for the sheet and sheet package processing factors were taken for the calculation of the losses in the iron:

- 1,6 – for the calculation of the basic losses in the stator sheet package,
- 2,2 – for the calculation of the additional pulsation losses,
- 2,2 – for the calculation of surface losses on the stator and
- 3,8 – for the calculation of surface losses on the rotor [8].

From the magnetic flux definition for the m_s phase winding, it ensues that, in the induction motor, besides the basic harmonic, also occurs the system of higher harmonics and is divided into the direct and the inverse harmonics system [1] and [9] which can be defined by the expression:

$$\nu = (2g_s m_s + 1)p, \quad g_s = 0,\ \pm1,\ \pm2,\ \ldots \tag{16}$$

Zbog reakcije armature za svaki harmonik statorskog protjecanja slijedi niz harmonika rotorskog protjecanja [8]:

Due to the armature reaction, each stator magnetic flux harmonic is followed by a series of rotor magnetic flux harmonics [8]:

$$\mu = g_r Q_r + \nu, \quad g_r = 0,\ \pm1,\ \pm2,\ \ldots \tag{17}$$

Na temelju (16) i (17) za promatrani trofazni asinkroni motor s tri para polova dobiva se niz harmonika prikazanih u tablici 3.

Based on (16) and (17), a series of harmonics shown in Table 3 is gained for the studied three-phase induction motor with three pole pairs.

Tablica 3 – Sustav nadharmonika magnetskog polja statora (ν) i rotora (μ), za motor s tri para polova ($p = 3$)
Table 3 – System of higher stator (ν) and rotor (μ) magnetic field harmonics for a three-pole pairs motor ($p = 3$)

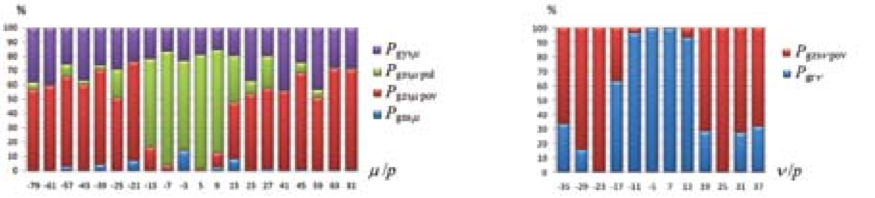
ν/p	μ/p			
1	–21	23	–43	45
–17	–39	5	–61	27
19	–3	41	–25	63
–35	–57	–13	–79	9
37	15	59	–7	81

Nadalje, prema izrazima za gubitke iz trećeg poglavlja [5] za odabrani su motor izračunati dodatni gubici u statoru i rotoru, te su prikazani u slici 9. Pri tome su prikazani sljedeći gubici:

$P_{\mathrm{gys}\,\mu}$ – gubici u jarmu statora,
$P_{\mathrm{gzs}\,\mu\,\mathrm{pul}}$ – pulzacijski gubici u zubima statora,
$P_{\mathrm{gzs}\,\mu\,\mathrm{pov}}$ – površinski gubici u zubima statora,
$P_{\mathrm{g\,ns}\,\mu}$ – gubici u statorskom namotu,
$P_{\mathrm{gzs}\,\nu\,\mathrm{pov}}$ – površinski gubici u zubima rotora,
$P_{\mathrm{gr}\,\nu}$ – gubici u rotorskom kavezu.

Furthermore, according to the expression for the losses from the third chapter [5], for the selected motor, additional stator and rotor losses were chosen and shown in Figure 9. Thereat the following losses are shown:

$P_{\mathrm{gys}\,\mu}$ – losses in the stator yoke,
$P_{\mathrm{gzs}\,\mu\,\mathrm{pul}}$ – pulsation losses in stator teeth,
$P_{\mathrm{gzs}\,\mu\,\mathrm{pov}}$ – surface losses in stator teeth,
$P_{\mathrm{g\,ns}\,\mu}$ – stator winding losses,
$P_{\mathrm{gzs}\,\nu\,\mathrm{pov}}$ – surface losses in rotor teeth,
$P_{\mathrm{gr}\,\nu}$ – losses in the rotor cage.



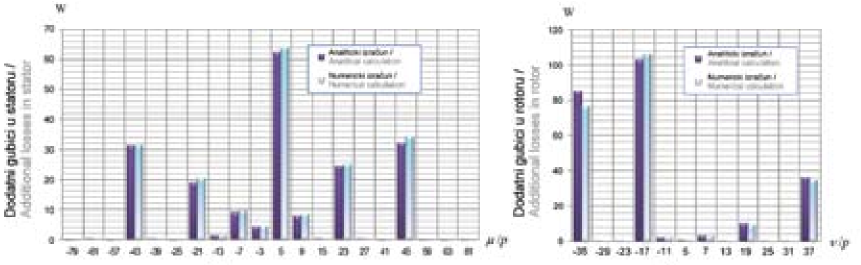
a)
Harmonici rotorskog magnetskog protjecanja
u statoru ovisno o harmonicima rotorskog protjecanja /
Rotor magnetic flux harmonics
in stator depending on the rotor magnetic flux harmonics

b)
Harmonici statorskog magnetskog protjecanja
u rotoru ovisno o harmonicima statorskog protjecanja /
Stator magnetic flux harmonics
in rotor depending on the stator magnetic flux harmonics

Slika 9 — Prikaz udjela pojedinih gubitaka u ukupnim dodatnim gubicima
Figure 9 — Overview of the share of certain losses in the total additional losses:

Numeričkim proračunom polja metodom konačnih elemenata i iterativnim postupkom opisanim u 4. poglavlju dobiva se raspodjela polja u motoru kao funkcija vremena, te se razvojem u Fourierov red izračunato polje rastavlja na komponente, prema harmonicima koji su prikazani u tablici 3. Usporedba ukupnih dodatnih gubitaka u statoru dobivenih analitičkim izračunom s vrijednostima dobivenih numeričkim postupkom za pojedine harmonike rotorskog protjecanja dana je na slici 10a), a usporedba ukupnih dodatnih gubitaka u rotoru dobivenih analitičkim izračunom s vrijednostima dobivenih numeričkim postupkom za pojedine harmonike statorskog protjecanja dana je na slici 10b).

The numerical calculation of the field by virtue of the finite element method and the iterative procedure described in Chapter 4, a distribution of the fields in the motor is obtained as a function of time and the field, calculated by elaboration into the Fourier series, is analysed into components, according to the harmonics shown in Table 3. The comparison of total additional losses in the stator gained by analytical calculation with the values gained by virtue of the numerical procedure for certain rotor flux harmonics is given in Figure 10a), and the comparison of total additional losses in the rotor gained by virtue of the analytical calculation with the values gained by virtue of the numerical procedure for certain stator flux harmonics is given in Figure 10b).



a)
Raspodjela dodatnih gubitaka u statoru ovisno o
harmonicima rotorskog protjecanja /
Distribution of additional losses in stator depending
on the rotor magnetic harmonics

b)
Raspodjela dodatnih gubitaka u rotoru ovisno o
harmonicima statorskog protjecanja /
Distribution of additional losses in rotor depending
on the stator magnetic harmonics

Slika 10 — Usporedba dodatnih gubitaka dobivenih analitičkim izračunom s vrijednostima dobivenih numeričkim postupkom za pojedine harmonike protjecanja
Figure 10 — Comparison of additional losses gained by analytical calculation with the values gained by virtue of the numerical procedure for certain flux harmonics

7 ZAKLJUČAK

Utjecaj geometrije lima na gubitke vrtložnih struja u pravokutnim zubima gotovo su egzaktno određeni iz rezultantnog polja u zubima, koje uzrokuje harmonik magnetske indukcije u zračnom rasporu. Izvod je načinjen uz pretpostavke μ_{Fe}= konst. i κ_{Fe}= konst., iz čega je izvedeno da se ukupni gubici vrtložnih struja u pravokutnim zubima mogu razdvojiti na pulzacijske i površinske gubitke, što je i do sada rađeno u poznatoj literaturi [10] i [11], ali bez dokaza.

Na kraju analitičkog modela izračuna dane su upute kako se za zube svih oblika mogu odrediti ukupni gubici u zubima. Za to je potrebno uzeti u obzir histerezne gubitke u limovima, te korekcije zbog potiskivanja toka u limovima, prigušenja toka u zubima za pulzacijske gubitke i korekcije zbog obrade lima i paketa limova.

Vrednovanje analitičkog modela izračuna potvrđeno je usporedbom s mjerenjima gubitaka u praznom hodu kaveznih asinkronih motora. Za dva motora snage 11 kW i 7,5 kW, izračunati su gubici u praznom hodu, te uspoređeni s odgovarajućim mjerenjima. Pokazano je da se izračunati ukupni gubici praznoga hoda dobro slažu s mjerenjima, a odstupanja se mogu objasniti nedostatnim (ulaznim) podacima. To se u prvom redu odnosi na stvarne gubitke magnetiziranja ugrađenoga lima, jer se računalo s garantiranim iznosima za specifične gubitke lima proizvođača, a zatim i na stvarnu (izvedenu) veličinu zračnog raspora, zbog čega je prikazana promjena dodatnih gubitaka u ovisnosti o širini otvora utora. Također, rezultati mjerenja i računa pokazuju da su dodatni gubici u praznom hodu tzv. naponski ovisni dodatni gubici značajan dio ukupnih gubitaka u praznom hodu. To se najbolje može vidjeti na dijagramima koji prikazuju ovisnost gubitaka zbog poprečnih struja o kontaktnom otporu i skošenju kaveza.

Odstupanje numeričkog od analitičkog izračuna dodatnih gubitaka za promatrani asinkroni motor je oko 10 %, čime je potvrđeno stajalište da analitički pristup određivanja dodatnih gubitaka ima određenu prednost pred numeričkim metodama proračuna, s obzirom da taj pristup pretpostavlja poznavanje uzroka i mehanizama nastajanja gubitaka, a izvedene formule daju uvid u utjecajnost pojedinih podataka motora. Za kvalitetan numerički izračun potrebno je puno više vremena iz razloga konstrukcije motora, mreženja modela, te samog iterativnog postupka proračuna. Analitički izračun je u tome puno brži, ali glavni nedostatak analitičkog modela izračuna u odnosu na numerički izračun je da zahtijeva inženjersko iskustvo projektiranja, u smislu određivanja koe-

7 CONCLUSION

The impact of the sheet geometry on eddy current losses in the rectangular teeth is determined with almost exact precision from the resultant field in the teeth caused by the magnetic induction harmonic in the air gap. The extraction is done under the assumptions μ_{Fe}= konst. and κ_{Fe}= konst., from which it is derived that the total eddy current losses in rectangular teeth may be divided into pulsation and surface losses, which has been done so far in the known literature [10] and [11], but without proof.

At the end of the analytical calculation model, instructions are given about teeth of all forms being apt for determination of total losses in the teeth. This requires taking into consideration the hysteresis losses in the sheets and the corrections because of the suppression of the flow in the sheets, the attenuation of the flow in the teeth for pulsation losses and corrections due to sheet and sheet package processing.

The valuation of the analytical calculation model is confirmed by the comparison with the measurements of losses in the idle running of the squirrel-cage induction motors. For two motors with 11 kW and 7,5 kW power, losses are calculated in idle running and compared with adequate measurements. It has been shown that total calculated losses of idle running agree well with the measurements, and the deviations may be explained by insufficient (input) data. This primarily concerns the actual magnetizing losses for the inbuilt sheet because guaranteed values for specific producer's sheet losses was counted on, as well as the actual (derived) size of the air gap, because of which the change of additional losses was shown depending on the slot opening width. Moreover, measurement and calculation results show that additional losses in idle running, so-called voltage-dependent additional losses, are a significant part of the total losses in idle running. This can be best seen in the diagrams which show the dependency of losses, due to transverse currents, on contact resistance and cage skew.

Deviation of the numerical from the analytical calculation of additional losses for the studied induction motor is about 10 %, which confirms the standpoints that the analytical approach to the determination of additional losses has certain advantage compared to the numerical calculation methods, considering that the approach assumes knowing the cause and mechanisms of loss occurrence, and the derived formulas provide insight into the impact of certain motor data. A quality numerical calculation requires much more time because of the motor construction, model networking and the iterative calculation process itself. The analytical calculation is much faster in this process, but the main disadficijenata kojima se uzimaju u obzir da je izračun pravljen za pravokutni zub, kao i pripadajuće faktore obrade lima.

Mogućnost analize dodatnih gubitaka u ovisnosti o vrijednosti kontaktnog otpora za različite vrijednosti skošenja je velika prednost analitičkog pristupa pri istraživanju dodatnih gubitaka, koja osobito pomaže pri samom projektiranju motora, gdje se odluka o broju utora i skošenju rotorskog kaveza zasniva prvenstveno na iskustvima samog projektanta.

vantage of the analytical calculation model compared to the numerical calculation is that it requires engineering experience in designing, in the sense of determination of coefficients by which it is taken into consideration that the calculation was done for a rectangular tooth, as well as the pertaining sheet processing factors.

The possibility of analysis of additional losses depending on the contact resistance value for different skew values is a great advantage of the analytical approach when additional losses are researched, and it is especially helpful with the very motor design where the decision on the number of slots and the skew of the rotor cage is based primarily on the experiences of the designer himself/herself.

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ODREĐIVANJE MATRICE KOEFICIJENATA REDUKCIJE SUSTAVA KABELSKIH VODOVA

DETERMINATION OF THE POWER CABLES SYSTEM REDUCTION COEFFICIENT MATRIX

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U radu su prezentirane izvorne teorijske podloge matematičkog modela za određivanje matrice koeficijenata redukcije sustava kabelskih vodova. Riječ je o novom i posve općenitom matematičkom modelu koji može uvažiti proizvoljan broj i raspored sustava jednožilnih kabela složenih u trokutnom snopu. Dotična matrica koeficijenata redukcije uračunava, naime, stvarni (potpuni) elektromagnetski utjecaj koji vlada među pripadnim kabelskim vodovima, u uvjetima nastupa jednopolnoga kratkog spoja. Za matricu koeficijenata redukcije značajno je da njeni elementi ovise isključivo o elektromagnetskim i geometrijskim značajkama samih kabelskih vodova, o njihovom smještaju te o geofizikalnim svojstvima njihove trase, kao i o frekvenciji struja koje teku kabelskim vodovima. Primjena ovdje razvijenog modela omogućava daleko točniji proračun raspodjele struja u sustavu kabelskih vodova nego li je to moguće primjenom pojedinačnih faktora redukcije nazočnih kabelskih vodova. Istodobno, razvijeni model je jednostavan za primjenu i posve općenit. Primjena prezentirane teorije i razvijenog matematičkog modela prikazana je i na primjeru općeg sustava kabelskih vodova nazivnog napona 110 kV.

The work presents original theoretical bases of the mathematical model for the determination of the power cables system reduction coefficient matrix. The matter at hand is a new and completely general mathematical model which can take into consideration an arbitrary number and arrangement of a single-core cable system arranged in a treefoil formation. As a matter of fact, the concerned reduction coefficient matrix takes into consideration the real (full) electromagnetic impact which dominates the pertaining power cables, in the conditions of occurrence of one-pole short circuit. The reduction coefficient matrix is characterized by having elements dependant exclusively on electromagnetic and geometrical properties of the very power cables, their positioning and on the geophysical properties of their route, as well as on the frequency of the currents flowing through the power cables. The application of the model deliberated here enables a far more accurate estimation of the current distribution in the power cables system than would be possible by applying separate reduction factors of the present power cables. At the same time, the deliberated model is simple for application and entirely general. The application of the presented theory and the developed mathematical model is also shown on the example of the general system of power cables with nominal voltage 110 kV.

Ključne riječi: elektromagnetska sprega; jednopolni kratki spoj; koeficijent redukcije; matrica; sustav kabelskih vodova
Key words: electromagnetic coupling; matrix; one-pole short circuit; power cables system; reduction coefficient

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1 UVOD

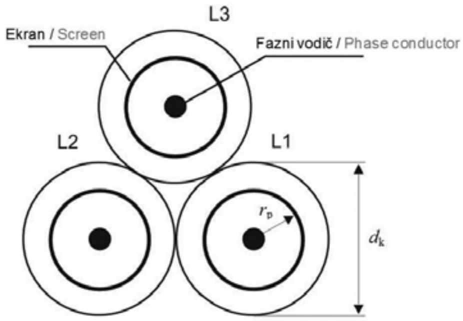
Razvitak većih urbanih područja i porast potrošnje električne energije u njima zahtijevaju primjenu kabelskih vodova sve viših nazivnih napona. Radi se redovito o sustavima kabelskih vodova koji dijelom ili u cijelosti imaju zajedničke kabelske trase. Ovi kabelski vodovi izvode se danas gotovo isključivo od jednožilnih kabela, s krutom izolacijom (umreženi polietilen – XLPE). Ovi kabeli sastoje se od faznog vodiča, koji se izrađuje od bakra ili aluminija, metalnog ekrana te poluvodljivih slojeva ispod i iznad izolacije. Osim toga, iznad ekrana oni u pravilu imaju bubrivu vrpcu i aluminijski laminat, za uzdužno i poprečno zapiranje prodora vlage. Naime, izolacija od umreženog polietilena je veoma osjetljiva na utjecaj vlage (nastup tzv. vodenih grančica). Konačno slijedi vanjski plašt jednožilnog kabela, koji se često izvodi od HDPE (polietilen velike gustoće), [1].

Kabelski vod se sastoji od tri spomenuta jednožilna kebala, koji se najčešće polažu u trokutnom snopu i pritom se međusobno dotiču. Njihov poprečni presjek grafički je ilustriran na slici 1.

1 INTRODUCTION

The development of larger urban areas and increased consumption of electricity in those areas require the application of power cables of increasingly higher nominal voltages. Those are regularly power cables systems which have common cable routes partly or in full. Today, these power cables are constructed almost exclusively of single-core cables with solid insulation (cross-linked polyethylene – XLPE). These cables consist of a phase conductor which is made of copper or aluminium, a metal screen and semiconductor layers over and under the insulation. Besides, above the screen, these usually have a swelling strip and aluminium lamination for longitudinal and transverse prevention of humidity penetration. Namely, the cross-linked polyethylene insulation is highly sensitive to the impact of humidity (the appearance of the so-called water twigs). Finally, there is the outer sheet of the single-core cable which is often made of HDPE (high-density polyethylene), [1].

The power cable consists of the three above mentioned single-core cables which are most usually laid in a trefoil formation and mutually touching thereat. Their transverse cross-section is graphically illustrated in Figure 1.



Slika 1 — Poprečni presjek kabelskog voda sastavljenog od jednožilnih kabela u trokutnom snopu
Figure 1 — Transverse intersection of the power cable consisting of one-core cables in a triangular truss

Oznake primijenjene na slici 1 imaju sljedeća značenja:

L1, L2 i L3 – faze dotičnog kabelskog voda,
r_p – srednji polumjer metalnog ekrana,
d_k – vanjski promjer jednožilnog kabela.

S obzirom da je ovdje riječ o kabelskim vodovima viših nazivnih napona (npr. 110 kV), oni pripadaju mreži koja radi s izravno uzemljenim zvjezdištima energetskih transformatora. Zbog toga spoj faznog vodiča sa zemljom u takvoj mreži predstavlja jednopolni kratki spoj. Mreža je ovdje galvanska veza spomenutih kabelskih vodova i pripadnih postrojenja istog nazivnog napona i frekvencije.

The symbols used in Figure 1 have the following meanings:

L1, L2 i L3 – phases of the concerned power cable,
r_p – mean radius of the metal screen,
d_k – outer diameter of the single-core cable.

Considering the fact that the matter at hand are power cables of higher nominal voltage (e.g. 110 kV), they belong to the network which operates with solidly earthed power transformer neutrals. Therefore, the circuit of the phase conductor and the ground in such a network represent a one-pole short circuit. The network is here a galvanic connection of the above power cables and the pertaining switchyards of the same nominal voltage and frequency.

Navedeni jednopolni kratki spoj (JKS) je praćen velikim strujama kvara. Riječ je o izrazito nesimetričnom kvaru, kod kojeg se razvijaju sustavi struja i napona direktnog, inverznog i nultog redoslijeda. Kod promatranog kabelskog voda, odgovarajuća nulta struja jednaka je sljedećem izrazu, [2]:

The said one-pole short circuit (OSC) is accompanied by large fault currents. The matter at hand is a greatly asymmetric fault at which current and voltage systems of direct, inverse and zero sequence develop. In the analysed power cable, the pertaining zero current is equal to the following expression, [2]:

$$\underline{I}_0 = \frac{1}{3} \cdot \left(\underline{I}_{\mathrm{L}1} + \underline{I}_{\mathrm{L}2} + \underline{I}_{\mathrm{L}3} \right), \tag{1}$$

gdje su $\underline{I}_{\mathrm{L}1}$, $\underline{I}_{\mathrm{L}2}$ i $\underline{I}_{\mathrm{L}3}$ struje dotičnog kvara u faznim vodičima $\mathrm{L}1$, $\mathrm{L}2$ i $\mathrm{L}3$ kabelskog voda. One se dobivaju proračunom JKS-a u pripadnoj mreži. Za struje nultog redoslijeda je značajno da se zatvaraju pripadnim sustavom uzemljenja, kao i samom zemljom.

U konkretnom slučaju, pripadni sustav uzemljenja sastoji se od uzemljivača pojedinih postrojenja koji čine promatranu mrežu i metalnih ekrana nazočnih kabelskih vodova uzemljenih na oba kraja. Metalni ekrani, dakle, povezuju uzemljivače susjednih postrojenja. Ne dolazi pritom do odvođenja dijela struje JKS-a s metalnog ekrana u zemlju, jer je vanjski plašt (omotač) ovih kabela izrađen od HDPE. On ove kabele svrstava u skupinu tzv. u odnosu na zemlju izoliranih kabela.

Pri nastupu jednopolnoga kratkog spoja popratna raspodjela struja kvara u pripadnom sustavu uzemljenja, kao i u samoj zemlji, uspostavlja se u skladu s nazočnom elektromagnetskom spregom i potencijalima uzemljivača. U tom smislu, u situaciji pojedinačnih kabelskih vodova koji imaju vlastite kabelske trase, odgovarajuća raspodjela struje kvara u zemlji duž njihove trase, koja je posljedica elektromagnetske sprege, određuje se sljedećim izrazom, [3]:

where $\underline{I}_{\mathrm{L}1}$, $\underline{I}_{\mathrm{L}2}$ and $\underline{I}_{\mathrm{L}3}$ are currents of the concerned fault in phase conductors $\mathrm{L}1$, $\mathrm{L}2$ and $\mathrm{L}3$ of the power cable. These are obtained by calculation of the OSC in the relevant network. Zero-sequence currents are characterized by the fact that they are closed by the pertaining earthing system as well as the ground itself.

In this particular case, the pertaining earthing system consists of the earthing grid of certain switchyards which make up the observed network and metal screens of the present power cables earthed at both ends. The metal screens therefore connect the earthing grids of neighbouring switchyards. Thereat, the abduction of part of the OSC current from the metal screen into the ground does not take place because the outer cable sheath (jacket) is made of HDPE. These cables are, hence, regarded as isolated in regards to the surrounding soil.

When the one-pole short circuit occurs, the accompanying distribution of fault currents in the pertaining earthing system, as well as in the ground itself, is established in accordance with the present electromagnetic coupling and the potentials of the grounding units. In that sense, in the situation of separate power cables which have own cable routes, adequate distribution of fault currents in the ground along their route which is the consequence of the electromagnetic coupling is determined according to the following expression, [3]:

$$\underline{I}_{\mathrm{z}} = \underline{r} \cdot 3\underline{I}_0 \tag{2}$$

pri čemu je $\underline{r}$ koeficijent redukcije dotičnog kabelskog voda. On se ovdje određuje pomoću sljedećeg izraza, [3], [4] i [5]:

whereat $\underline{r}$ is the reduction coefficient of the concerned power cable. It is determined here by virtue of the following expression, [3], [4] and [5]:

$$\underline{r} = \frac{\dfrac{R_{\mathrm{p}1}}{3}}{\dfrac{R_{\mathrm{p}1}}{3} + \dfrac{\omega\mu_0}{8} + \mathrm{j}\dfrac{\omega\mu_0}{2\pi} \cdot \ln\left(\dfrac{658}{\sqrt[3]{r_{\mathrm{p}} \cdot d_{\mathrm{k}}^2}} \cdot \sqrt{\dfrac{\rho}{f}} \right)} \tag{3}$$

u kojem novouvedene veličine znače:

- R_{P1} – jedinični djelatni otpor metalnog ekrana, Ω/km,
- ω – kružna frekvencija struje JKS-a, dana izrazom $\omega = 2\pi f$, gdje je $f = 50$ Hz,
- μ_0 – permeabilnost slobodnog prostora, koja iznosi $4\pi \cdot 10^{-4}$ Vs/A·km,
- ρ – prosječna električna otpornost (specifični električni otpor) tla duž trase promatranog kabelskog voda, Ωm.

Jedinični djelatni otpor ekrana, uvažavajući i njegovu temperaturnu ovisnost, može se odrediti sljedećim izrazom:

in which the newly-introduced elements mean:

- R_{P1} – per-unit resistance of the metal screen, Ω/km,
- ω – circular frequency of the OSC current presented by the expression $\omega = 2\pi f$, where $f = 50$ Hz, (3)
- μ_0 – permeability of the vacuum which amounts to $4\pi \cdot 10^{-4}$ Vs/A·km,
- ρ – mean specific soil electrical resistance along the route of the observed power cable, Ωm.

The per-unit resistance of the screen, taking into consideration also its temperature dependence, can be determined by virtue of the following expression:

$$R_{p1} = \rho_{cu} \cdot \frac{1\,000}{S_p} \cdot k_1 \cdot k_\upsilon \qquad (4)$$

pri čemu su:

- ρ_{cu} – električna otpornost (specifični električni otpor) bakra pri temperaturi 20 °C,
- S_p – ukupna površina presjeka ekrana jednožilnog kabela, mm^2,
- k_1 – koeficijent kojim se uzima u račun povećanje duljine žica ekrana radi uvijanja,
- k_υ – koeficijet kojim se uzima u obzir utjecaj temperature na električni otpor ekrana, ovaj koeficijent određuje se prema IEC preporukama, [6].

U urbanim (gradskim) područjima radi se redovito o sustavima kabelskih vodova, koji dijelom ili u cijelosti imaju zajedničke kabelske trase. Tijekom spomenutog JKS-a dolazi stoga do međusobne elektromagnetske sprege među navedenim kabelskim vodovima, što utječe na popratnu raspodjelu struja kvara u njihovom sustavu uzemljenja, kao i u samoj zemlji. Zbog toga u ovom slučaju, dakako, nije moguće popratno strujno stanje u zemlji valjano opisati pojedinačnim (vlastitim) koeficijentima redukcije svakog od pripadnih kabelskih vodova, već samo odgovarajućom matricom koeficijenata redukcije promatranog sustava kabelskih vodova. Korištenje pojedinačnih (vlastitih) koeficijenata redukcije svakog od pripadnih kabelskih vodova, uz zanemarivanje međusobne elektromagnetske sprege među njima, u ovakvim slučajevima bi dovelo do velikih pogrešaka u izračunu raspodjele struja u zemlji.

Određivanje spomenute matrice koeficijenata redukcije stoga je upravo predmet ovoga rada. U njemu će se prezentirati, između ostalog, i teorijske podloge matematičkog modela proračuna

whereat it is as follows:

- ρ_{cu} – specific electrical resistance of copper at the temperature of 20 °C,
- S_p – total surface area of the single-core cable screen cross-section, mm^2,
- k_1 – the coefficient by which increased length of the screen wires is taken into consideration because of the wrapping,
- k_υ – the coefficient by which the impact of temperature on the screen electrical resistance is taken into consideration; this coefficient is determined following IEC recommendations, [6].

Urban (city) areas regularly have power cables systems with common cable routes partly or in full. During the said OSC, reciprocal electromagnetic coupling between the power cables occurs and this affects the pertaining distribution of fault currents in their earthing system and in the ground itself as well. Therefore, in this case, it is of course impossible to describe accurately the pertaining current situation in the ground by individual (self) reduction coefficients of each of the pertaining power cables but only by the adequate reduction coefficient matrix of the observed power cables system. Using individual (self) reduction coefficients of each of the pertaining power cables, along with ignoring the reciprocal electromagnetic coupling between them, in these cases, would bring about significant errors in the calculation of currents distribution in the ground.

Therefore, it is exactly the determination of the said reduction coefficient matrix that is the subject of this work. It will present, inter alia, theoretical matrice koeficijenata redukcije na primjeru općeg sustava kabelskih vodova. Valja naglasiti da je primjena matrice koeficijenata redukcije novina u odnosu na dosadašnje metode određivanja raspodjele struja jednopolnoga kratkog spoja u pasivnim dijelovima kabelskih sustava te popratnih struja u zemlji.

2 TEORIJSKE PODLOGE

Na slici 2 prikazan je primjer općeg sustava kabelskih vodova i njima incidentna postrojenja A, B, C i D s pripadnim energetskim transformatorima i nadomjesnim mrežama. Dotični sustav sastoji se, dakle, od $n = 5$ kabelskih vodova. Njihova numeracija prikazana je također na slici 2. Ona je odabrana sasvim proizvoljno. Navedeni kabelski vodovi sačinjeni su od jednožilnih kabela i položeni su u trokutnom snopu. Njihovi metalni ekrani uzemljeni su na oba kraja.

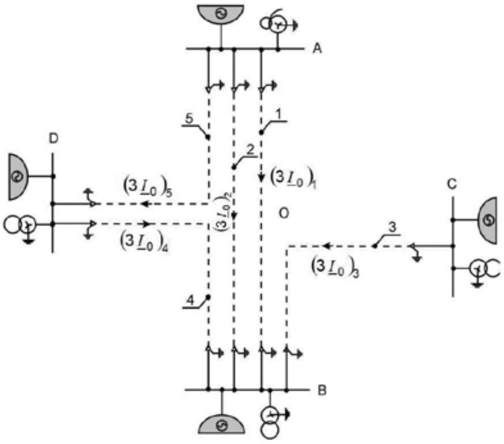
Osim toga, na slici 2 označeni su i smjerovi trostrukih nultih struja $(3\underline{I}_0)_i,\ i = 1, 2, ..., n,$ koje teku faznim vodičima navedenih kabelskih vodova. Ovi smjerovi dotičnih struja odgovaraju nastupu JKS-a u postrojenju B. Valja navesti da se vrijednosti dotičnih struja dobiju posebnim proračunom u pripadnoj mreži, kojoj je sustav prikazan na slici 2 tek jedan mali dio. Ove struje se stoga ovdje mogu smatrati poznatima.

bases of the mathematical model for the calculation of the reduction coefficient matrix on the example of the general power cables system. It should be pointed out that the application of the reduction coefficient matrix is new in relation to former methods for determination of the distribution of one-pole short circuit currents in the passive parts of the cable systems and the accompanying currents in the ground.

2 THEORETICAL BASES

Figure 2 shows the example of the general power cables system and their incidental switchyards A, B, C and D with pertaining power transformers and substitute networks. The concerned system consists therefore of $n = 5$ power cables. Their numeration is also shown in Figure 2. It has been chosen completely arbitrarily. The said power cables are made of single-core cables and laid in treefoil formation. Their metal screens are earthed at both ends.

Besides that, Figure 2 indicates also the directions of the triple zero currents $(3\underline{I}_0)_i,\ i = 1, 2, ..., n,$ which flow through phase conductors of the said power cables. These directions of the concerned currents coincide with the occurrence of the OSC in the B switchyard. It should be stated that the values of the concerned currents are obtained by special calculation in the pertaining network, of which the system shown in Figure 2 is only a small part. These currents can therefore be considered known here.



Slika 2 — Jednopolna shema općeg sustava kabelskih vodova i njima incidentnih postrojenja A, B, C i D s pripadnim energetskim transformatorima i nadomjesnim mrežama

Figure 2 — One-pole scheme of the general power cables system and their incidental switchyards A, B, C and D with pertaining power transformers and substitute networks

Budući da se navedeni kabelski vodovi sastoje od po tri jednožilna kabela složena u trokutnom snopu i da su njihovi metalni ekrani uzemljeni na

As the said power cables consist of three single-core cables arranged in treefoil formation and as their metal screens are earthed at both ends, each oba kraja, moguće je svaki kabelski vod zamijeniti s ekvivalentnim kabelom, kojem je metalni ekran određen sljedećim parametrima:

R_eq1 – jedinični djelatni otpor metalnog ekrana ekvivalentnog kabela, Ω/km, u skladu s (3) njegova je vrijednost:

power cable can be replaced with the equivalent cable the metal screen of which is determined by the following parameters:

R_eq1 – per-unit resistance of the equivalent cable metal screen, Ω/km, in accordance with (3), its value is:

$$R_\mathrm{eq1}=\frac{R_\mathrm{p1}}{3}\,, \tag{5}$$

r_eq – polumjer metalnog ekrana ekvivalentnog kabela, m, također prema (3), on iznosi:

r_eq – radius of the equivalent cable metal screen, m; also according to (3), it amounts to:

$$r_\mathrm{eq}=\sqrt[3]{r_\mathrm{p}\cdot d_\mathrm{k}^2}\;. \tag{6}$$

Temeljem relacija (5) i (6) uočava se da je ekvivalentiranje pojedinog kabelskog voda izvršeno u skladu s metodom srednjih geometrijskih udaljenosti. Ovaj korak smanjuje potreban broj jednadžbi sustava te pojednostavnjuje sam matematički model, uz istodobno osiguranje visoke točnosti rezultata proračuna. Naime, ekvivalentiranje kabelskog sustava prema (5) i (6) ne utječe na preciznost dobivenih rezultata proračuna. Ovo se može lako provjeriti.

U uvjetima nastupa JKS-a i danih struja $(3\underline{I}_0)_i$, $i=1,\ 2,\ \ldots,\ n$, javit će se zbog elektromagnetske sprege i odgovarajuće struje u metalnim ekranima spomenutih kabelskih vodova, kao i struje u zemlji. Strujno stanje u metalnim ekranima spomenutih kabelskih vodova može se pritom odrediti metodom konturnih struja (metoda petlji). Može se postaviti sljedeća matrična jednadžba:

Based on the relations (5) and (6), it is evident that the replacement of the particular power cable was done in accordance with the mean geometrical distances method. This step reduces the necessary number of system equations and simplifies the mathematical model itself while ensuring high accuracy of the calculation results at the same time. Namely, the replacement of the cable system according to (5) and (6) does not affect the accuracy of the obtained calculation results. This can be verified easily.

In the conditions of occurrence of OSC and the given currents $(3\underline{I}_0)_i$, $i=1,\ 2,\ \ldots,\ n$, because of the electromagnetic coupling, also adequate currents in the metal screens of the said power cables will appear as well as currents in the grounds. The current condition in the metal screens of the said power cables can then be determined by virtue of the contour currents method (the loop method). The following matrix equation can appear:

$$\underline{\boldsymbol{Z}}_\mathrm{p}\cdot\vec{\underline{I}}_\mathrm{p}=\vec{\underline{E}}_\mathrm{p} \tag{7}$$

u kojoj su:

$\underline{\boldsymbol{Z}}_\mathrm{p}$ – matrica vlastitih i međusobnih impedancija petlji, koju čine metalni ekrani spomenutih kabelskih vodova s utjecajem povratnog puta kroz tlo; riječ je o kvadratnoj matrici reda (n, n),

$\vec{\underline{I}}_\mathrm{p}$ – vektor konturnih struja, koje teku metalnim ekranima spomenutih kabelskih vodova; općeniti oblik ovog vektora može se zapisati na sljedeći način:

in which it is as follows:

$\underline{\boldsymbol{Z}}_\mathrm{p}$ – the matrix of self and mutual loops impedances consisting of metal screens of the said power cables with the impact of the return path through the ground; the matter at hand is a (n, n) square matrix.

$\vec{\underline{I}}_\mathrm{p}$ – the vector of contour currents which flow through the metal screens of the said power cables; the general form of this vector can be written as follows:

$$\underline{\vec{I}}_{\mathrm{p}} = \begin{bmatrix} {}^{1}\underline{I}_{\mathrm{p}} \\ \cdot \\ \cdot \\ \cdot \\ {}^{i}\underline{I}_{\mathrm{p}} \\ \cdot \\ \cdot \\ \cdot \\ {}^{n}\underline{I}_{\mathrm{p}} \end{bmatrix} \tag{8}$$

$\underline{\vec{E}}_{\mathrm{p}}$ – vektor uzdužnih elektromotornih sila induciranih u metalnim ekranima spomenutih kabelskih vodova uslijed struja $\left(3\underline{I}_0\right)_i$, $i = 1,\ 2,\ \ldots,\ n$, koje teku faznim vodičima kabelskih vodova.

Matrica vlastitih i međusobnih impedancija petlji $\underline{\boldsymbol{Z}}_{\mathrm{p}}$ je simetrična u odnosu na svoju glavnu dijagonalu. Njeni dijagonalni i izvan dijagonalni članovi računaju se respektivno pomoću sljedećih izraza:

$\underline{\vec{E}}_{\mathrm{p}}$ – the vector of longitudinal electromotive forces induced in metal screens of the said power cables due to the currents $\left(3\underline{I}_0\right)_i$, $i = 1,\ 2,\ \ldots,\ n$, which flow through the phase conductors of the power cables.

The matrix of self and mutual loop impedances $\underline{\boldsymbol{Z}}_{\mathrm{p}}$ is symmetrical in relation to its main diagonal. Its diagonal and extra-diagonal members are calculated respectively by virtue of the following expressions:

$${}^{ii}\underline{Z}_{\mathrm{p}} = {}^{ii}\underline{Z}_{\mathrm{p1}} \cdot l_i, \tag{9}$$

$${}^{ik}\underline{Z}_{\mathrm{p}} = {}^{ik}\underline{Z}_{\mathrm{p1}} \cdot l_{ik}, \tag{10}$$

pri čemu su prema [3] i [7]:

whereat according to [3] and [7] it follows:

$${}^{ii}\underline{Z}_{\mathrm{p1}} = R_{\mathrm{eq1}} + \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\frac{\rho}{f}}\right), \tag{11}$$

$${}^{ik}\underline{Z}_{\mathrm{p1}} = \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{d_{ik}} \cdot \sqrt{\frac{\rho}{f}}\right), \tag{12}$$

gdje je:

l_i – duljina i-tog, $i = 1, 2, \ldots, n$, kabelskog voda, km,

l_{ik} – duljina paralelnog vođenja između i-tog i k-tog, $k = 1, 2, \ldots, n$, kabelskog voda, km, ona, dakako, može biti jednaka nuli; primjerice, sa slike 2 se uočava da je $l_{35} = 0$, pri čemu je i odgovarajuća međusobna impedancija također jednaka nuli,

d_{ik} – srednja geometrijska udaljenost između i-tog i k-tog kabelskog voda, m.

Značenje ostalih veličina u izrazima (11) i (12) već prije je objašnjeno u Uvodu, te u izrazima (5) i (6). Valja navesti da su vlastite impedancije uvijek pozitivne, dok međusobne impedancije mogu biti pozitivne ili negativne. To ovisi o usvojenim smjerovima odgovarajućih konturnih struja. Ako su smjerovi odgovarajućih konturnih struja isti, tada

where it is as follows:

l_i – he length of the i^{th}, $i = 1, 2, \ldots, n$, power cable, km,

l_{ik} – the length of parallel guidance between the i^{th} and the k^{th}, $k = 1, 2, \ldots, n$, power cable, km; it can of course be equal to zero; for example, Figure 2 reveals that $l_{35} = 0$ whereat the pertaining reciprocal impedance is also equal to zero,

d_{ik} – mean geometrical distance between the i^{th} and the k^{th} power cable, m.

The meaning of the other elements in the expression (11) and (12) has already been explained in the Introduction and in the expressions (5) and (6). It should be stated that self impedances are always positive while mutual impedances can be either positive or negative. This depends on the adopted directions of the pertaining contour currents. If je pripadna međusobna impedancija pozitivna. U protivnom, ukoliko su smjerovi odgovarajućih konturnih struja suprotni, tada je pripadna međusobna impedancija negativna.

Vektor uzdužnih elektromotornih sila iz relacije (7), induciranih u metalnim ekranima kabelskih vodova, može se odrediti sljedećom matričnom jednadžbom:

the directions of the pertaining contour currents are the same, then the pertaining mutual impedance is positive. In the opposite case, if the directions of the pertaining contour currents are opposite, then the pertaining mutual impedance is negative.

The vector of longitudinal electromotive forces, induced in the power cables metal screens, from the relation (7), can be determined by virtue of the following matrix equation:

$$\vec{\underline{E}}_{\mathrm{p}} = \underline{\boldsymbol{Z}}_{\mathrm{m}} \cdot 3\vec{\underline{I}}_0 \ , \tag{13}$$

pri čemu su:

- $\underline{\boldsymbol{Z}}_{\mathrm{m}}$ – matrica međusobnih impedancija petlji, koje čine metalni ekrani i fazni vodiči spomenutih kabelskih vodova s utjecajem povratnog puta kroz tlo; radi se također o kvadratnoj matrici reda (n, n),
- $3\vec{\underline{I}}_0$ – vektor trostrukih nultih struja, koje teku faznim vodičima spomenutih kabelskih vodova; elementi ovog vektora su, dakle, struje prikazane na slici 2, a njegov oblik je općenito sljedeći:

whereat it is as follows:

- $\underline{\boldsymbol{Z}}_{\mathrm{m}}$ – the matrix of mutual loops impedances consisting of metal screens and phase conductors of the said power cables with the impact of the return path through the ground; the matter at hand is also a (n, n) square matrix,
- $3\vec{\underline{I}}_0$ – the vector of triple zero currents which flow through the phase conductors of the said power cables; thus, the elements of this vector are the currents shown in Figure 2 and its form is generally the following:

$$3\vec{\underline{I}}_0 = \begin{bmatrix} \left(3\vec{\underline{I}}_0\right)_1 \\ \vdots \\ \left(3\vec{\underline{I}}_0\right)_i \\ \vdots \\ \left(3\vec{\underline{I}}_0\right)_n \end{bmatrix} . \tag{14}$$

Matrica međusobnih impedancija petlji $\underline{\boldsymbol{Z}}_{\mathrm{m}}$ je također simetrična u odnosu na svoju glavnu dijagonalu. Njeni dijagonalni i izvandijagonalni elementi računaju se respektivno pomoću sljedećih izraza:

The matrix of mutual loop impedances $\underline{\boldsymbol{Z}}_{\mathrm{m}}$ is also symmetrical in relation to its main diagonal. Its diagonal and extra-diagonal elements are calculated respectively by virtue of the following expressions:

$${}^{ii}\underline{Z}_{\mathrm{m}} = {}^{ii}\underline{Z}_{\mathrm{m1}} \cdot l_i \ , \tag{15}$$

$${}^{ik}\underline{Z}_{\mathrm{m}} = {}^{ik}\underline{Z}_{\mathrm{m1}} \cdot l_{ik} \tag{16}$$

gdje su:

whereat it is as follows:

$${}^{ii}\underline{Z}_{\mathrm{m1}} = \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\frac{\rho}{f}}\right) \tag{17}$$

$$ {}^{ik}\underline{Z}_{\mathrm{m1}} = \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{d_{ik}} \cdot \sqrt{\frac{\rho}{f}} \right) \tag{18} $$

Na kraju valja spomenuti da je smjer konturnih struja koje teku metalnim ekranima kabelskih vodova, dan prema relaciji (8), usvojen takav da one teku u suprotnom smjeru od odgovarajućih struja $3\underline{I}_0$. Dakle, smjer struje ${}^{1}\underline{I}_{\mathrm{p}}$ je suprotan od smjera struje $\left(3\underline{I}_0\right)_1$, itd.

Uvrštenjem matrične jednadžbe (13) u matričnu jednadžbu (7) dobiva se:

Finally, it should be stated that the direction of contour currents which flow through the power cable metal screens, given according to the relation (8), is taken to be such as to allow them flowing contrary to the pertaining currents $3\underline{I}_0$. Therefore, the direction of the current ${}^{1}\underline{I}_{\mathrm{p}}$ is opposite to the direction of the current $\left(3\underline{I}_0\right)_1$, etc.

By introducing the matrix equation (13) into the matrix equation (7), the result is:

$$ \underline{\boldsymbol{Z}}_{\mathrm{p}} \cdot \vec{\underline{I}}_{\mathrm{p}} = \underline{\boldsymbol{Z}}_{\mathrm{m}} \cdot 3\vec{\underline{I}}_0 \tag{19} $$

Iz dotične matrične jednadžbe slijedi:

From the concerned matrix equation it ensues:

$$ \vec{\underline{I}}_{\mathrm{p}} = \underline{\boldsymbol{Z}}_{\mathrm{p}}^{-1} \cdot \underline{\boldsymbol{Z}}_{\mathrm{m}} \cdot 3\vec{\underline{I}}_0 \tag{20} $$

Nadalje, odgovarajuće struje u zemlji mogu se odrediti sljedećom matričnom jednadžbom:

Furthermore, the pertaining currents in the ground can be determined by the following matrix equation:

$$ \vec{\underline{I}}_{\mathrm{z}} = 3\vec{\underline{I}}_0 - \vec{\underline{I}}_{\mathrm{p}} \tag{21} $$

gdje je $\vec{\underline{I}}_{\mathrm{z}}$ vektor odgovarajućih struja u zemlji, koji ima sljedeći opći oblik:

where $\vec{\underline{I}}_{\mathrm{z}}$ is the vector of pertaining currents in the earth and it has the following form:

$$ \vec{\underline{I}}_{\mathrm{z}} = \begin{bmatrix} {}^{1}\underline{I}_{\mathrm{z}} \\ \cdot \\ \cdot \\ \cdot \\ {}^{i}\underline{I}_{\mathrm{z}} \\ \cdot \\ \cdot \\ \cdot \\ {}^{n}\underline{I}_{\mathrm{z}} \end{bmatrix} . \tag{22} $$

Daljnjim uvrštenjem matrične jednadžbe (20) u (21) dobiva se:

Further introduction of the matrix equation (20) into (21) results in:

$$ \vec{\underline{I}}_{\mathrm{p}} = \left(\boldsymbol{E} - \underline{\boldsymbol{Z}}_{\mathrm{p}} \cdot \underline{\boldsymbol{Z}}_{\mathrm{m}} \right) 3\vec{\underline{I}}_0 \tag{23} $$

pri čemu je $\boldsymbol{E}$ – jedinična matrica reda (n, n). Ova matrica u svojoj glavnoj dijagonali ima jedinice.

whereat $\boldsymbol{E}$ is the (n, n) unit matrix. This matrix has units in its main diagonal. All of its extra-diagonal

Svi njeni izvandijagonalni elementi jednaki su nuli.

Uvede li se sljedeća supstitucija:

elements equal zero.

If the following substitution is introduced:

$$\boldsymbol{\underline{r}} = \boldsymbol{E} - \boldsymbol{\underline{Z}}_{\mathrm{p}}^{-1} \cdot \boldsymbol{\underline{Z}}_{\mathrm{m}} \ , \tag{24}$$

može se matrična jednadžba (23) napisati u sljedećem obliku:

the matrix equation (23) can be written in the following form:

$$\vec{\underline{I}}_{\mathrm{z}} = \boldsymbol{\underline{r}} \cdot 3\vec{\underline{I}}_0 \ . \tag{25}$$

Pritom je $\boldsymbol{\underline{r}}$ – matrica koeficijenata redukcije promatranog sustava kabelskih vodova. Riječ je ponovno o kvadratnoj matrici reda (n, n). Za dotičnu matricu je značajno da njeni elementi ovise o elektromagnetskim i geometrijskim značajkama metalnih ekrana kabelskih vodova, zatim o njihovom smještaju (konfiguraciji), kao i o geofizikalnim svojstvima (električnoj otpornosti tla) njihove trase. Oni također ovise i o frekvenciji struja koje teku spomenutim kabelskim vodovima. U uvjetima nastupa JKS-a riječ je, dakako, o frekvenciji $f = 50$ Hz.

Na temelju prezentirane teorije izrađen je odgovarajući računalni program. Isti je napisan u programskom jeziku Fortran 95, [8]. Pomoću razvijenog računalnog programa može se, dakle, odrediti odgovarajuća matrica koeficijenata redukcije po volji složenog sustava kabelskih vodova, kao i popratna raspodjela struja u zemlji za zadana strujna opterećenja faznih vodiča navedenih kabelskih vodova.

Na kraju, zanimljivo je navesti da je matrična jednadžba dana izrazom (25) oblikom slična izrazu (2), koji se odnosi na slučaj samo jednog kabelskog voda. Analogno tomu, matrična jednadžba dana izrazom (24) u slučaju samo jednog kabelskog voda poprima sljedeći oblik:

Thereat, $\boldsymbol{\underline{r}}$ is the reduction coefficient matrix of the observed power cables system. The matter at hand is again a (n, n) square matrix. The concerned matrix is characterized by its elements being dependant on electromagnetic and geometrical properties of power cable metal screens, on their positioning (configuration), as well as on the geophysical properties (specific ground electrical resistance) of their route. These also depend on the frequency of currents which flow through the said power cables. In the conditions of occurrence of OSC, the concerned frequency is of course $f = 50$ Hz.

Based on the presented theory, adequate computer software has been developed. It is written in the Fortran 95 programming language, [8]. By virtue of the developed computer programme, the adequate reduction coefficient matrix can of course be determined as required by the complex power cables system, as well as the pertaining distribution of currents in the ground for the given current loads of the said power cables' phase conductors.

Finally, it is interesting to state that the matrix equation given by the expression (25) has a form similar to expression (2) which relates to the case of only one power cable. Analogously, the matrix equation given by the expression (24) in case of only one power cable assumes the following form:

$$\underline{r} = 1 - \frac{\underline{Z}_{\mathrm{m}}}{\underline{Z}_{\mathrm{p}}} \ . \tag{26}$$

U skladu s izrazima (9), (11), (15) i (17) ovdje je:

In accordance with the expressions (9), (11), (15) and (17), here it is as follows:

$$\frac{\underline{Z}_{\mathrm{m}}}{\underline{Z}_{\mathrm{p}}} = \frac{\dfrac{\omega \cdot \mu_0}{8} + \mathrm{j}\dfrac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\dfrac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\dfrac{\rho}{f}}\right)}{R_{\mathrm{eq1}} + \dfrac{\omega \cdot \mu_0}{8} + \mathrm{j}\dfrac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\dfrac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\dfrac{\rho}{f}}\right)} \ . \tag{27}$$

Uvrštenjem izraza (27) u (26) slijedi:

The introduction of the expression (27) into (26) results in:

$$\underline{r} = \frac{R_{\mathrm{eq1}}}{R_{\mathrm{eq1}} + \frac{\omega \cdot \mu_0}{8} + \mathrm{j}\frac{\omega \cdot \mu_0}{2\pi} \cdot \ln\left(\frac{658}{r_{\mathrm{eq}}} \cdot \sqrt{\frac{\rho}{f}}\right)} \quad . \tag{28}$$

Dakle, uz (5) i (6) izraz (28) je istovjetan izrazu (3), koji je prije naveden kao koeficijent redukcije samo jednog kabelskog voda.

3 PRIMJER PRORAČUNA

Kao primjer proračuna odabran je sustav kabelskih vodova prikazan na slici 2. Neka se radi o kabelskim vodovima nazivnog napona 110 kV, koji se sastoje od jednožilnih kabela s faznim vodičem od aluminija presjeka 1 000 mm^2. Njihova izolacija je od umreženog polietilena, a metalni ekran od helikoidno motanih okruglih bakrenih žica ukupnog presjeka 95 mm^2. Jedinični djelatni otpor i srednji polumjer metalnog ekrana respektivno iznose $R_{\mathrm{P1}} = 0{,}226\ \Omega/\mathrm{km}$ i $r_{\mathrm{P1}} = 37$ mm, [9]. Vanjski plašt jednožilnog kabela je od HDPE, a njegov vanjski promjer iznosi $d_{\mathrm{k}} = 84$ mm.

Temeljem navedenih podataka, te izraza (5) i (6), slijedi da je fiktivni ekvivalentni kabel, svakog od kabelskih sustava, dan sljedećim veličinama $R_{\mathrm{eq\,1}} = 0{,}075\ \Omega/\mathrm{km}$ i $r_{\mathrm{eq}} = 0{,}0964$ m.

Konfiguracija i numeracija navedenih kabelskih vodova prikazani su također na slici 2. Neka se radi o sljedećim njihovim duljinama: $l_1 = l_2 = 3{,}5$ km, $l_3 = 6$ km, $l_4 = 4{,}5$ km i $l_5 = 5$ km.

Prema slici 2, kabelski vodovi 1, 2 i 5 na potezu A – O imaju zajedničku kabelsku trasu duljine 2 km. To isto imaju i kabelski vodovi 1, 2, 3 i 4 na potezu B – O u duljini 1,5 km, te kabelski vodovi 4 i 5 na potezu D – O u duljini 3 km. Nadalje, međusobni razmak između susjednih kabelskih vodova smještenih u zajedničke kabelske trase iznosi 0,6 m.

Konačno, prosječna električna otpornost (prosječni specifični električni otpor) tla duž trasa navedenih kabelskih vodova neka je svugdje isti i iznosi $\rho = 200\ \Omega\mathrm{m}$.

Korištenjem spomenutog računalnog programa dobivena je matrica koeficijenata redukcije promatranog sustava kabelskih vodova. Uz navedene podatke, ova matrica je izračunata za $f = 50$ Hz i $\mu_0 = 4\pi \cdot 10^{-4}$ Vs/A·km. Ona je prikazana izrazom (29):

Therefore, with (5) and (6), the expression (28) is equal to the expression (3) which has been stated above as the reduction coefficient of only one power cable.

3 CALCULATION EXAMPLE

As an example of calculation, the power cables system shown in Figure 2 was chosen. Let us say that these are power cables of nominal voltage of 110 kV and consisting of single-core cables with an aluminium phase conductor with the cross-section area of 1 000 mm^2. Their insulation is made of cross-linked polyethylene and a metal screen of helicoidally wrapped circular copper wires of total cross-section area of 95 mm^2. Per-unit resistance and mean metal screen radius respectively amount to $R_{\mathrm{P1}} = 0{,}226\ \Omega/\mathrm{km}$ and $r_{\mathrm{P1}} = 37$ mm, [9]. The outer single-core able sheath is made of HDPE and its outer diameter amounts to $d_{\mathrm{k}} = 84$ mm.

Based on the stated data and based on the expressions (5) and (6), it ensues that the fictive equivalent cable, of each of the cable systems, is given by the following dimensions $R_{\mathrm{eq\,1}} = 0{,}075\ \Omega/\mathrm{km}$ and $r_{\mathrm{eq}} = 0{,}0964$ m.

The configuration and the numeration of the said power cables are also shown in Figure 2. Let us say that their lengths are as follows: $l_1 = l_2 = 3{,}5$ km, $l_3 = 6$ km, $l_4 = 4{,}5$ km and $l_5 = 5$ km.

According to Figure 2, the power cables 1, 2 and 5 on the A – O stretch have a common 2 km long cable route. The same pertains to the power cables 1, 2, 3, and 4 on the B – O stretch in the length of 1,5 km and power cables 4 and 5 on the D – O stretch in the length of 3 km. Furthermore, the interspacing between the neighbouring power cables positioned in common cable routes amounts to 0,6 m.

Finally, let us say that the mean specific ground electrical resistance along the routes of the said power cables is the same everywhere and amounts to $\rho = 200\ \Omega\mathrm{m}$.

Use of the said computer programme enabled the reduction coefficient matrix of the observed power cables system. With the mentioned data, this matrix was calculated for $f = 50$ Hz and $\mu_0 = 4\pi \cdot 10^{-4}$ Vs/A·km. It is shown by the expression (29):

$$\underline{r} = \begin{bmatrix} 0{,}123 - j0{,}261 & -0{,}094 + j0{,}148 & -0{,}014 + j0{,}033 & -0{,}015 + j0{,}049 & -0{,}018 + j0{,}054 \\ -0{,}094 + j0{,}148 & 0{,}149 - j0{,}277 & -0{,}001 + j0{,}017 & -0{,}058 + j0{,}080 & -0{,}058 + j0{,}083 \\ -0{,}010 + j0{,}024 & -0{,}001 + j0{,}012 & 0{,}030 - j0{,}134 & -0{,}004 + j0{,}017 & 0{,}003 - j0{,}006 \\ -0{,}013 + j0{,}043 & -0{,}050 + j0{,}070 & -0{,}004 + j0{,}020 & 0{,}089 - j0{,}211 & 0{,}074 - j0{,}126 \\ -0{,}015 + j0{,}047 & -0{,}051 + j0{,}073 & 0{,}003 - j0{,}007 & 0{,}074 - j0{,}126 & 0{,}087 - j0{,}209 \end{bmatrix} . \quad (29)$$

Primjera radi, korištenjem izraza (3), odnosno (27), odgovarajući koeficijent redukcije jednog od navedenih kabelskih vodova iznosi:

To exemplify, the use of the expression (3), that is, (27), the pertaining reduction coefficient of one of the said power cables amounts to:

$$\underline{r} = 0{,}118\angle -78{,}7^\circ . \quad (30)$$

U tablici 1 (stupci 3 i 4) prikazane su raspodjele trostrukih nultih struja kroz fazne vodiče navedenih kabelskih vodova, pri neistodobnim nastupima JKS-a u postrojenjima A, B, C i D. Osim toga, u istoj tablici (stupci 5 i 6) prikazane su i odgovarajuće trostruke nulte struje kroz fazne vodiče navedenih kabelskih vodova za usvojeno njihovo usmjerenje prema slici 2, također pri neistodobnim nastupima JKS-a u spomenutim postrojenjima. Naime, matrica koeficijenata redukcije promatranog sustava kabelskih vodova određena je za usvojeno usmjerenje trostrukih nultih struja prema slici 2.

Table 1 (columns 3 and 4) shows the distributions of the triple zero currents through the phase conductors of the said power cables at non-simultaneous occurrences of the OSC in the switchyards A, B, C and D. Besides that, the same table (columns 5 and 6) also shows the pertaining triple zero currents through the phase conductors of the said power cables for their direction adopted according to Figure 2, also at non-simultaneous occurrences of the OSC in the said switchyards. Namely, the reduction coefficient matrix of the observed power cables system is determined for the adopted direction of triple zero currents according to Figure 2.

Tablica 1 – Raspodjela trostrukih nultih struja kroz fazne vodiče navedenih kabelskih vodova (KB), pri neistodobnim nastupima JKS-a u postrojenjima A, B, C i D
Table 1 – Distribution of triple zero currents through the phase conductors of the said power cables (KB) at non-simultaneous occurrences of the OSC in the switchyards A, B, C and D

Mjesto JKS-a / OSC location	Oznaka KB-a / KB symbol	Raspodjela struja kvara / Fault currents distribution			
		Od – do / From - to	$3\underline{I}_0$, kA ∠°	Od – do / From - to	$3\underline{I}_0$, kA ∠°
A	1	B – A	$2{,}5\angle -85^\circ$	A – B	$2{,}5\angle 95^\circ$
	2	B – A	$2{,}5\angle -85^\circ$	A – B	$2{,}5\angle 95^\circ$
	3	C – B	$2{,}0\angle -75^\circ$	C – B	$2{,}0\angle -75^\circ$
	4	B – D	$1{,}1\angle -80^\circ$	D – B	$1{,}1\angle 100^\circ$
	5	D – A	$1{,}9\angle -66^\circ$	A – D	$1{,}9\angle 114^\circ$
B	1	A – B	$8{,}6\angle -77^\circ$	A – B	$8{,}6\angle -77^\circ$
	2	A – B	$8{,}6\angle -77^\circ$	A – B	$8{,}6\angle -77^\circ$
	3	C – B	$2{,}7\angle -87^\circ$	C – B	$2{,}7\angle -87^\circ$
	4	D – B	$3{,}4\angle -109^\circ$	D – B	$3{,}4\angle -109^\circ$
	5	A – D	$1{,}4\angle -160^\circ$	A – D	$1{,}4\angle -160^\circ$
C	1	A – B	$4{,}0\angle -75^\circ$	A – B	$4{,}0\angle -75^\circ$
	2	A – B	$4{,}0\angle -75^\circ$	A – B	$4{,}0\angle -75^\circ$
	3	B – C	$10{,}1\angle -82^\circ$	C – B	$10{,}1\angle 98^\circ$
	4	D – B	$1{,}0\angle -107^\circ$	D – B	$1{,}0\angle -107^\circ$
	5	A – D	$0{,}9\angle -177^\circ$	A – D	$0{,}9\angle 177^\circ$
D	1	A – B	$3{,}2\angle -114^\circ$	A – B	$3{,}2\angle -114^\circ$
	2	A – B	$3{,}2\angle -114^\circ$	A – B	$3{,}2\angle -114^\circ$
	3	C – B	$1{,}9\angle -80^\circ$	C – B	$1{,}9\angle -80^\circ$
	4	B – D	$9{,}0\angle -104^\circ$	D – B	$9{,}0\angle 76^\circ$
	5	A - D	$10{,}9\angle -56^\circ$	A – D	$10{,}9\angle -56^\circ$

Daljnjom primjenom spomenutog računalnog programa, korištenjem raspodjela trostrukih nultih struja danih u tablici 1 (stupac 6), dobivene su odgovarajuće raspodjele struja u zemlji duž navedenih kabelskih vodova, u slučajevima neistodobnih nastupa JKS-a u postrojenjima A, B, C i D. Rezultati dotičnih proračuna predočeni su u tablici 2.

Further application of the said computer programme and the use of the distributions of the triple zero currents given in Table 1 (column 6) result in the pertaining distributions of the currents in the ground along the said power cables, in cases of non-simultaneous occurrence of the OSC in the switchyards A, B, C and D. The results of the concerned calculations are presented in Table 2.

Tablica 2 – Raspodjela popratnih struja u zemlji duž navedenih kabelskih vodova (KB), pri neistodobnim nastupima JKS-a u postrojenjima A, B, C i D

Table 2 – Distribution of accompanying currents through the said power cables (KB) at non-simultaneous occurrences of the OSC in the switchyards A, B, C and D

Oznaka KB-a / KB symbol	Od – do / From - to	Struje $\underline{I_z,\ \mathrm{A}\angle^{\circ}}$ pri nastupima JKS-a u / currents at occurrence of the OSC in:			
		A	B	C	D
1	A – B	$204\angle 11{,}8^{\circ}$	$757\angle 220^{\circ}$	$795\angle 215{,}4^{\circ}$	$682\angle 125^{\circ}$
2	A – B	$178\angle -21{,}8^{\circ}$	$850\angle 235^{\circ}$	$630\angle 222{,}3^{\circ}$	$1\,106\angle 140^{\circ}$
3	C – B	$376\angle 205^{\circ}$	$63\angle 109{,}5^{\circ}$	$1\,549\angle 21{,}6^{\circ}$	$352\angle 209^{\circ}$
4	D – B	$243\angle 54{,}6^{\circ}$	$843\angle 93{,}9^{\circ}$	$401\angle 105{,}7^{\circ}$	$2\,089\angle -31^{\circ}$
5	A – D	$249\angle 61{,}5^{\circ}$	$922\angle 80{,}1^{\circ}$	$629\angle 66{,}8^{\circ}$	$1\,704\angle -79^{\circ}$

Valja navesti da se struje u tablici 2 mogu dalje iskoristiti, primjerice, za određivanje opasnih napona koji se mogu inducirati u telekomunikacijskim (TK) vodovima sa žičanim vodičima i metalnim masama (kovinski cjevovodi i sl.), smještenim u području elektromagnetskog utjecaja promatranog sustava kabelskih vodova.

It should be mentioned that the currents in Table 2 can be used further, for example, for the determination of dangerous voltages which can be induced in telecommunication (TC) cables with wire conductors and metal masses (metal pipelines, etc.), located in the area of electromagnetic impact of the observed power cables system.

4 ZAKLJUČAK

U sustavu kabelskih vodova, u uvjetima nastupa jednopolnoga kratkog spoja, dolazi do međusobne elektromagnetske sprege među pripadnim kabelskim vodovima. To utječe na raspodjelu popratne struje kvara u pripadnom sustavu uzemljenja, kao i u samoj zemlji.

Dotična raspodjela struja kvara ne može se egzaktno odrediti korištenjem pojedinačnih koeficijenata redukcije svakog od pripadnih kabelskih vodova, već samo uporabom odgovarajuće matrice koeficijenata redukcije promatranog sustava kabelskih vodova.

Teorijske podloge određivanja dotične matrice koeficijenata redukcije izvorno su prikazane u ovom radu. Za matricu koeficijenata redukcije je značajno da njeni elementi ovise o:

- elektromagnetskim i geometrijskim značajkama metalnih ekrana pripadnih kabelskih vodova, zatim o
- njihovom smještaju (konfiguraciji), te o

4 CONCLUSION

In the power cables system, in the conditions of occurrence of one-pole short circuit, there occurs mutual electromagnetic coupling between the pertaining power cables. That affects the distribution of the accompanying fault current in the pertaining earthing system, as well as in the ground itself.

The concerned distribution of the fault currents cannot be determined exactly by using individual reduction coefficients of each of the pertaining power cables but only by using the adequate reduction coefficient matrix of the observed power cables system.

Theoretical bases for the determination of the concerned reduction coefficient matrix are shown originally in this work. The reduction coefficient matrix is characterized by having elements dependant on:

- electromagnetic and geometric properties of the metal screens of the pertaining power ca-

- geofizikalnim svojstvima njihove trase, kao i o
- frekvenciji struja koje teku dotičnim kabelskim vodovima.

U radu je također prikazana i primjena iznesene teorije na primjeru općeg sustava kabelskih vodova nazivnog napona 110 kV. Izračunate struje u zemlji mogu se dalje iskoristiti npr. za određivanje opasnih induciranih napona u telekomunikacijskim vodovima sa žičanim vodičima i drugim metalnim masama, smještenim u području elektromagnetskog utjecaja sustava kabelskih vodova.

Na kraju valja naglasiti da se do iste raspodjele struja u pripadnom sustavu uzemljenja, kao i u samoj zemlji može doći i drugim metodama i postupcima. Primjerice, primjenom tehnike konačnih elemenata na razmatrani sustav, i sl. Prednost ovog pristupa, korištenjem matrice koeficijenata redukcije sustava kabelskih vodova, iskazuje se u njegovoj jednostavnosti, uz istodobnu iznimno visoku točnost.

bles, and then on
- their positioning (configuration), and on
- the geophysical properties of their route, as well as on
- the frequency of the currents flowing through the concerned power cables.

The work also depicts the application of the presented theory on the example of the general system of power cables with nominal voltage of 110 kV. The calculated currents in the earth can further serve, e.g. for the determination of dangerous induced voltages in telecommunication cables with wire conductors and other metal masses, located in the area of electromagnetic impact of the power cables system.

Finally, it needs to be pointed out that the same distribution of currents in the pertaining earthing system, as well as in the ground itself, can also be obtained by other methods and procedures. For example, by applying the finite element technique on the observed system, etc. The advantage of this approach of using the reduction coefficient matrix of the power cables system is in its simplicity and extremely high accuracy.

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