

ENERGIA

**JOURNAL
OF ENERGY**

IZDAVAČ

Hrvatska elektroprivreda d.d., Zagreb

SUIZDAVAČI

Sveučilište u Zagrebu, Fakultet elektrotehnike i računarstva
Ministarstvo gospodarstva, rada i poduzetništva

ZA IZDAVAČA

Mr. sc. Ivan Mravak

POMOĆ U IZDAVANJU

Ministarstvo znanosti, obrazovanja i športa

UREĐIVAČKI SAVJET

Mr. sc. Kažimir Vrankić, (predsjednik), Zagreb – doc. dr. sc. Ante Čurković, Zagreb – prof. dr. sc. Igor Dekanić, Zagreb – prof. dr. sc. Danilo Feretić, Zagreb – mr. sc. Nikica Grubišić, Zagreb – prof. dr. sc. Slavko Krajcar, Zagreb – doc. dr. sc. Željko Tomšić, Zagreb – doc. dr. sc. Mladen Zeljko, Zagreb

UREĐIVAČKI ODBOR

Glavni urednik – Mr. sc. Goran Slipac, Zagreb
Glavni tajnik – Mr. sc. Slavica Barta-Koštrun, Zagreb
Lektor – Šimun Čagalj, prof., Zagreb
Metrološka recenzija – Dragan Borojević, dipl. ing., Zagreb
Prijevod – Hrvatsko društvo znanstvenih i tehničkih prevoditelja – Prevoditeljski centar, Zagreb

UREDNIŠTVO I UPRAVA

HEP d.d. – Energija
Ulica grada Vukovara 37, 10000 Zagreb, Hrvatska
Telefoni: +385 (1) 6171291 i 6322641
Telefaks: +385 (1) 6322143
e-mail: goran.slipac@hep.hr; slavica.barta@hep.hr
www.hep.hrGodišnje izlazi 6 brojeva
Godišnja pretplata bez PDV-a (22%) iznosi:
– za pojedince 250 kn
– za poduzeća 400 kn
– za studente 60 kn
Žiro račun kod Zagrebačke banke broj:
2360000-1400129978Godišnja pretplata za inozemstvo iznosi USD 95.
Devizni račun:
Zagrebačka banka broj: 2000006299Grafičko uređenje omota – mr. sc. Kažimir Vrankić, Zagreb
Grafičko uređivanje – Bestias dizajn. d.o.o., Zagreb
Tisak – intergrafika d.o.o., ZagrebNaklada – 1 500 primjeraka
Godište 57(2008)
Zagreb, 2008
Brj 4., str. 371-478

Oglasi su veličine jedne stranice. Cijena oglasa je 3 000 kn bez PDV (22%).

PUBLISHED BY

Hrvatska elektroprivreda d.d., Zagreb

CO-PUBLISHED BY

University of Zagreb, Faculty of Electrical Engineering and Computing
Ministry of Economy, Labour and Entrepreneurship

PUBLISHER'S REPRESENTATIVE

Ivan Mravak, MSc

SUPPORTED BY

Ministry of Science, Education and Sport

EDITORIAL COUNCIL

Kažimir Vrankić, MSc, (Chairman), Zagreb – Assistant Prof Ante Čurković, PhD, Zagreb – Prof Igor Dekanić, PhD, Zagreb – Prof Danilo Feretić, PhD, Zagreb – Nikica Grubišić, MSc, Zagreb – Prof Slavko Krajcar, PhD, Zagreb – Assistant Prof Željko Tomšić, PhD, Zagreb – Assistant Prof Mladen Zeljko, PhD, Zagreb

EDITORIAL BOARD

Editor-in-chief – Goran Slipac, MSc, Zagreb
Secretary – Slavica Barta-Koštrun, MSc, Zagreb
Language Editor – Šimun Čagalj, prof., Zagreb
Metrology – Dragan Borojević, dipl. ing., Zagreb
Translation – Croatian Association of Scientific and Technical Translators – Croatian Translation Agency, Zagreb

HEAD OFFICE AND MANAGEMENT

HEP d.d. – Energija, Editorial Board
Ulica grada Vukovara 37, 10000 Zagreb, Hrvatska
Telephone: +385 (1) 6171291 i 6322641
Fax: +385 (1) 6322143
e-mail: goran.slipac@hep.hr; slavica.barta@hep.hr
www.hep.hrAppears 6 times a year.
Annual subscription fee excl. VAT (22 %):
– for individual subscribers HRK 250
– for companies HRK 400
– for students HRK 60
Number of fyro account whit Zagrebačka Banka:
2360000 – 1400129978Annual subscription fee for the overseas: USD 95.
Number of foreign currency account whit Zagrebačka Banka:
2000006299Cover design – Kažimir Vrankić, MSc, Zagreb
Graphic layout – Bestias Dizajn d.o.o., Zagreb
Printed by – Intergrafika d.o.o., ZagrebCirculation – 1 500 copies
Volume 57(2008)
Zagreb, 2008
No. 4., p. p. 371-478

Ads are the size of the page. The price of an ad is HRK 3 000 excl. VAT (22 %).

SADRŽAJ

Dokmanović, V.
EUROPSKA ISKUSTVA U SVEZI PRIHVATA PROIZVODNJE
ELEKTRICNE ENERGIJE VJETROELEKTRANA U ELEK-
TROENERGETSKI SUSTAV
(pregledni članak)

376-407

Mesić, M., Puharić, M., Škarica, D.
PRIMJENA LINIJSKIH ODVODNIKA PRENAPONA ZA
ZAŠTITU DALEKOVOĐA 110 kV STON - KOMOLAC OD
ATMOSFERSKIH PRAŽNJENJA
(prethodno priopćenje)

408-423

Kapetanović, I., Sarajlić, N., Tešanović, M., Kasumović, M.
NUMERICKO RJEŠAVANJE RASPODJELE ELEKTROMAG-
NETSKOG I TEMPERATURNOG POLJA ZRAČNOG TRANS-
FORMATORA
(prethodno priopćenje)

424-439

Sarajčev, I., Sarajčev, P., Vujević, S.
ODREĐIVANJE MEĐUSOBNOG OTPORA UZEMLJENJA
BLISKIH UZEMLJIVAČA
(prethodno priopćenje)

440-451

Kuzmanović, B., Baus, Z.
DINAMIČKA SVOJSTVA TIRISTORA
(pregledni članak)

452-475

Časopis je ubilježen u Ministarstvu znanosti, obrazovanja i
športa pod brojem 161 od 12.11.1992.Časopis je indeksiran u sekundarnom bibliografskom izvoru
INSPEC – The Institution of Electrical Engineering, England.

CONTENTS

Dokmanović, V.
EUROPEAN EXPERIENCE IN CONNECTION WITH THE INTE-
GRATION OF ELECTRICITY GENERATED BY WIND POWER
PLANTS INTO ELECTRICAL POWER SYSTEMS
(review article)*Mesić, M., Puharić, M., Škarica, D.*
APPLICATION OF LINE SURGE ARRESTERS IN THE PROTEC-
TION OF THE 110 kV STON - KOMOLAC TRANSMISSION LINE
FROM ATMOSPHERIC DISCHARGES
(preliminary information)*Kapetanović, I., Sarajlić, N., Tešanović, M., Kasumović, M.*
NUMERICAL SOLUTION FOR THE DISTRIBUTION OF THE
ELECTROMAGNETIC AND THERMAL FIELDS OF AN AIR-CORE
TRANSFORMER
(preliminary information)*Sarajčev, I., Sarajčev, P., Vujević, S.*
DETERMINATION OF THE MUTUAL GROUND RESISTANCE OF
ADJACENT GROUNDING GRIDS
(preliminary information)*Kuzmanović, B., Baus, Z.*
DYNAMIC PROPERTIES OF THYRISTORS
(review article)The journal is registered with the Ministry of Science, Education and
Sport under No. 161 since 12.11.1992The journal is indexed with the secondary reference source of
INSPEC – The Institution of Electrical Engineering, England.

UREĐIVAČKA POLITIKA

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

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

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

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

EDITORIAL POLICY

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

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

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

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

UVOD

INTRODUCTION

Poštovani čitatelji!

Pred sobom imate četvrti broj časopisa Energija u 2008. godini. Ova je godina za energetski sektor u Hrvatskoj posebno interesantna. U prvom redu je to poradi izrade Zelene knjige prilagodba i nadogradnja strategije energetskog razvitka Republike Hrvatske koja detaljnije definiira strukturu energetskog sektora Republike Hrvatske za sljedećih petnaestak godina te postavlja temelje razvoja energetskog sektora za sljedećih dvadeset i više godina. Praktički gledano, energetika u Hrvatskoj se nalazi na određenoj prekretnici i biti će vrlo zanimljivo kako će se odvijati postupak usvajanja prijedloga Zelene knjige, odnosno prihvaćanje temeljnih načela kao i predloženih rješenja i koncepcija. Časopis Energija pravo je mjesto za promociju, ali i kritičku analizu opredjeljenja u energetici pa vas pozivamo da u sljedećim brojevima iznesete svoja stajališta i kritičke osvrtne na današnja događanja.

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

- Europska iskustva u svezi prihvata proizvodnje električne energije vjetroelektrana u elektroenergetski sustav,
- Primjena linijskih odvodnika prenapona za zaštitu dalekovoda 110 kV Ston – Komolac od atmosferskih pražnjenja,
- Numeričko rješavanje raspodjele elektromagnetskog i temperaturnog polja zračnog transformatora,
- Određivanje međusobnog otpora uzemljenja bliskih uzemljivača,
- Dinamička svojstva tiristora.

U prvom članku u ovom broju časopisa Energija iznose se ponajprije podaci o očekivanju uloge vjetroelektrana u zadovoljenju elektroenergetske bilance u zemljama Europske unije i to kroz prirodne podatke o daljnjem razvoju i izgradnji vjetroelektrana, te institucionalno kroz posebne odluke Europske komisije. Posebno je važno analizirati tehničke uvjete priključenja vjetroelektrana na mrežu, jer se njima zapravo želi ne samo zadržati dostignuta razina kvalitete i sigurnosti opskrbe električnom energijom nego je i poboljšati. Nekoliko je važnih pitanja vezanih uz ovaj problem, ali je ipak temeljno pitanje kako omogućiti prihvata proizvodnje električne energije VE, kojom će se pokrivati više od četvrtine bruto potrošnje u Europskoj uniji 2030. godine, a da se ne ugrozi sigurnost pogona sustava, odnosno sigurnost opskrbe električnom energijom.

Drugi članak opisuje probleme i način zaštite 110 kV voda koji je poradi specifičnog položaja izložen atmosferskom

Dear Readers,

You have before you the fourth issue of the journal Energija for the year 2008. This year is particularly interesting for the energy sector in Croatia. In the first place, this is due to the preparation of the Green Book for Regulating and Upgrading the Energy Development Strategy of the Republic of Croatia, which defines the structure of the energy sector of the Republic of Croatia in detail for the next fifteen years and establishes the foundations for the development of the energy sector for the next twenty or more years. The energy sector in Croatia is at a turning point. It will be very interesting to see how the proposals of the Green Book will be adopted regarding the acceptance of the fundamental principles, proposed solutions and concepts. The journal Energija is the proper place for the promotion as well as for the critical analysis of energy decisions. We invite you to present your viewpoints and critiques on these current events in future issues.

In this issue of the journal Energija, we are presenting highly interesting articles from various specialized fields in electrical engineering:

- European Experience in Connection with the Integration of Electricity Generated by Wind Power Plants into Electrical Power Systems,
- Application of Line Surge Arresters in the Protection of the 110 kV Ston – Komolac Transmission Line from Atmospheric Discharges,
- Numerical Solution for the Distribution of the Electromagnetic and Thermal Fields of an Air-Core Transformer,
- Determination of the Mutual Ground Resistance of Adjacent Grounding Grids,
- Dynamic Properties of Thyristors.

In the first article in this issue of the journal Energija, data are presented on the anticipated role of wind power plants in achieving electricity balance in the countries of the European Union, including data on the further development and construction of wind power plants and special decisions by the European Commission. It is particularly important to analyze the technical conditions for the connection of wind power plants to grids because it is desired not only to retain the achieved level of quality and security of the electricity supply but also to improve it. There are several important questions in connection with this problem but the fundamental question is how to facilitate the integration of the energy generated by wind power plants, which will cover over a quarter of the gross consumption in the European Union in the year 2030, without endangering the security of system operation, i.e. the security of the electricity supply.

The second article describes the problems and manner of protection of a 110 kV transmission line due to its specific

pražnjenju. Naime, statistikom pogonskih događaja u prijenosnoj mreži koja se vodi od 1995. godine zabilježen je neuobičajeno veliki broj prisilnih zastoja dalekovoda 110 kV Ston – Komolac, koji su za posljedicu imali smanjenu pouzdanost pogona tog dijela prijenosne mreže i sigurnosti napajanja šireg dubrovačkog područja električnom energijom. Nakon ugradnje linijskih odvodnika prenapona, broj ispada kao i trajanje ispada dalekovoda iz pogona smanjio se u značajnoj mjeri. Ne treba posebno spominjati kako su rezultati navedeni u članku vrlo zanimljivi, a s obzirom da su u zaključku spomenuti i neki sljedeći koraci u ovom istraživanju, očekujemo u nekom od sljedećih brojeva i ostale rezultate koji će sasvim sigurno proizaći iz ovih istraživanja i biti vrlo interesantni za čitatelje časopisa Energija.

U ovom broju časopisa Energija imamo i temu vezanu uz analizu elektromagnetskih i termičkih pojava u metalnim dijelovima transformatora, što je važan korak u procesima projektiranja ovakvih uređaja. U radu se opisuje numeričko rješavanje raspodjele elektromagnetskog i temperaturnog polja zračnog transformatora metodom konačnih elemenata. Članak iznosi niz važnih zaključaka temeljenih na numeričkim proračunima, čija je točnost provjerena i nizom eksperimentalnih mjerenja, što potvrđuje osnovnu zamisao autora a to je opravdanost uvođenja i razvijanja ovakvih numeričkih proračuna za rješavanje ili analizu praktičnih problema.

Četvrti članak u ovom broju odnosi se na probleme uzemljivača odnosno problemu određivanja međusobnog otpora uzemljenja bliskih uzemljivača. Naime, kod bliskih uzemljivača javlja se značajna konduktivna sprega među njima, što vodi porastu ukupnog otpora uzemljenja pripadnog uzemljivačkog sustava. U članku je izveden izvorni analitički izraz za određivanje međusobnog otpora uzemljenja koji omogućava jednostavno izračunavanje pripadnog međusobnog otpora uzemljenja. Poznavanje međusobnog otpora uzemljenja je inače bitno za korektno određivanje raspodjele parcijalnih struja dozemnog kratkog spoja u pripadnom sustavu uzemljenja.

Posljednji članak dolazi iz specijalističkog područja upravljanja tiristorima. Pri izboru elemenata nekog strujnog kruga mora se voditi računa o režimu rada svakog elementa. To znači da za svaki element treba utvrditi dopuštene vrijednosti struje, napona i snage te radnu temperaturu. Prekoračenje bilo koje dopuštene vrijednosti obično dovodi do oštećenja elemenata. U radu se najprije razmatraju dinamička svojstva i karakteristike uključivanja, a zatim se detaljnije analiziraju efekti di/dt / dr . Na temelju dinamičkih svojstava isključenja tiristora predlaže se i odgovarajuća nadomjesna shema.

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

location in a zone where the intensity of the atmospheric discharge is high. Statistics on operational events in the transmission network since 1995 have recorded an unusually large number of forced outages of the 110 kV Ston – Komolac Transmission Line, resulting in a reduction in the reliability of the operation of that part of the transmission network and the security of the electricity supply of the greater Dubrovnik region. Following the installation of line surge arresters, significantly fewer and shorter outages were recorded. It is not necessary to mention that the results in the article are highly interesting. As several subsequent steps are mentioned in the conclusion, in future issues we anticipate further results that will certainly ensue from this investigation and be of great interest to the readers of the journal Energija.

In this issue of the journal Energija, we also have a topic in connection with an analysis of the electromagnetic and thermal phenomena in the metal parts of transformers, which is a significant step in the designing process. The article describes a numerical solution for the distribution of electromagnetic and thermal fields of an air-core transformer using the finite element method. The article presents a series of important conclusions based upon numerical calculations, confirmed by the results of a series of experimental measurements, which thereby confirm the justification for the introduction and development of such numerical calculations for the solution or analysis of practical problems.

The fourth article in this issue refers to the problems of the determination of the mutual ground resistance of adjacent grounding grids. Significant coupling occurs between adjacent grounding grids, which leads to an increase in the total ground resistance of the corresponding grounding system. The article presents the derivation of an original analytical expression for the determination of said mutual ground resistance, which facilitates its calculation. Knowing the mutual ground resistance is necessary for the correct determination of the distribution of partial ground fault currents in the corresponding grounding system.

The final article comes from the specialized area of thyristor control. When choosing the elements of an electrical circuit, it is necessary to take the operating mode of each element into account. This means that for each element it is necessary to determine the permissible values of current, voltage and power dissipation, as well as operating temperature range. Exceeding any of the permissible values generally leads to damage to the elements. The article first discusses the turn-on characteristics of thyristors and then analyzes the effects of di/dt / dr in detail. On the basis of the dynamic turn-off characteristics of thyristors, a corresponding equivalent diagram is proposed.

The high quality articles in this issue of the journal Energija are signed by authors from university communities as well as the field.

Editor-in-chief:
Goran Slipac, MSc

EUROPSKA ISKUSTVA U SVEZI PRIHVATA PROIZVODNJE ELEKTRIČNE ENERGIJE VJETROELEKTRANA U ELEKTROENERGETSKI SUSTAV EUROPEAN EXPERIENCE IN CONNECTION WITH THE INTEGRATION OF ELECTRICITY GENERATED BY WIND POWER PLANTS INTO ELECTRICAL POWER SYSTEMS

Vladimir Dokmanović, Zagreb, Hrvatska

U članku su izložena europska iskustva u svezi korištenja energije vjetra u proizvodnji električne energije. Istaknut je značaj optimizacije postojeće električne mreže, njeno pojačanje i proširenje, kao i izgradnja suvremene električne mreže za brži i učinkovitiji prihvata obnovljivih izvora energije.

Cilj članka je da se na temelju mnogih studijsko istraživačkih radova na temu prihvata električne energije vjetroelektrana u elektroenergetske sustave pojedinih zemalja ukaže na važnost i složenost ove problematike.

The article presents European experiences regarding the use of wind power in electricity production. Emphasis is placed upon the significance of optimizing, strengthening and expanding an existing electrical grid, as well as the construction of modern grids for the rapid and efficient integration of renewable energy sources. The goal of the article is to draw attention to the importance and complexity of this topic by utilizing the findings of numerous research studies on the integration of electricity from wind power plants into the electrical power systems of individual countries.

Ključne riječi: elektroenergetski sustav; mrežna pravila; obnovljivi izvori energije; operater vjetroelektrane; operator sustava; vjetroelektrane

Key words: electrical power system; grid codes; renewable energy sources; system operator; wind power plant operator; wind power plants



1 UVOD

U članku je izložena buduća uloga obnovljivih izvora energije u pokrivanju rastuće potrošnje električne energije u Europskoj uniji i u svijetu. Navode se odluke Europske Komisije o daljnjem razvoju obnovljivih izvora energije i korištenju energije vjetra u proizvodnji električne energije, te se ističe važnost prijenosne mreže u prihvatu proizvodnje vjetroelektrana (VE) u elektroenergetski sustav.

Uz to, navode se ciljevi tehničkih kriterija i zahtjeva na VE, koji se reguliraju mrežnim pravilima. Njima se želi ostvariti sigurnost pogona elektroenergetskog sustava i zadržati dostignuta kvaliteta isporuke električne energije potrošačima, ali i poticanje razvoja onih osobina VE, koje pridonose stabilnosti pogona elektroenergetskog sustava (EES-a) i što boljoj kompatibilnosti VE i sustava.

Cilj mrežnih pravila trebao bi biti i omogućavanje što većeg prihvata VE u sustav i poboljšanje integracijskih svojstava VE, odnosno izgradnja VE koje imaju istovjetne osobine poput konvencionalnih elektrana.

U članku su također izložena i najnovija iskustva europskih zemalja u korištenju energije vjetra u proizvodnji električne energije, a navedena su i najnovija istraživanja usmjerena na daljnje mogućnosti prihvata proizvodnje VE u sustave pojedinih zemalja.

Osnovno je pitanje kako omogućiti prihvata proizvodnje električne energije VE, kojom će se pokrivati više od četvrtine bruto potrošnje u Europskoj uniji 2030. godine, a da se ne ugrozi

1 INTRODUCTION

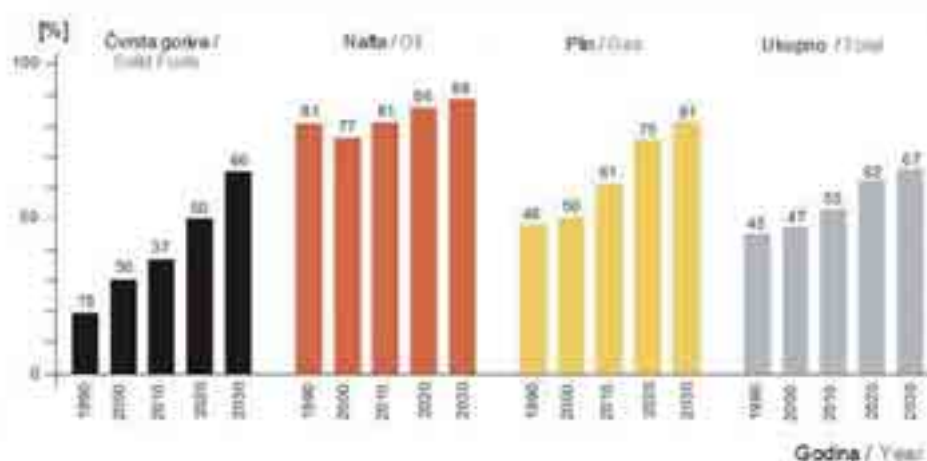
The article discusses the future role that renewable energy sources will play in covering growing electricity consumption in the European Union and the world. Decisions by the European Commission are cited on the further development of renewable energy sources, the use of wind power in the generation of electricity and the importance of the transmission grid in the integration of the power generated by wind power plants (WPPs) into the electrical power system.

Moreover, the goals of the technical criteria and requirements for WPPs, which are regulated by grid codes, are presented. The aim is to achieve secure operation of an electrical power system and maintain quality delivery of electricity to consumers, as well as to promote the development of those characteristics of WPPs that contribute to the stability of the operation of an electrical power system and optimal compatibility between the WPPs and the system.

The goal of grid codes should also be to facilitate the maximum integration of WPPs into a system and improve the integrational properties of WPPs, i.e. the construction of WPPs with the same characteristics as conventional power plants.

The article also presents the most recent experiences of European countries in the use of wind power for the generation of electrical power, including the most recent investigations into further possibilities for the integration of WPPs within the systems of individual countries.

A basic question is how to facilitate the integration of the electrical power produced by WPPs, which could cover over a quarter of the total consumption in the European Union in the year 2030, without endanger-



Slika 1 – Uvozna ovisnost Europske unije (EU25) od 1990. do 2030. godine [1]

Figure 1 – Import dependence of energy sources in the European Union (EU25) from 1990 to 2030 [1]

sigurnost pogona sustava, odnosno sigurnost opskrbe električnom energijom.

2 OPĆENITO O OPSKRBI ELEKTRIČNOM ENERGIJOM

Živimo u svijetu u kojem brzo raste potrošnja energije. Europa očekuje povećanje potrošnje električne energije za 50 % do 2030. godine. Kada se ne bi mijenjala europska energetska strategija, te bi godine europska uvozna ovisnost o energiji iznosila oko 67 % (slika 1).

Prošlo je vrijeme sigurne opskrbe energijom. Dani jeftine i dovoljno raspoložive energije su iza nas. Ovo stoljeće bit će ispunjeno borbom svjetskih ekonomskih blokova za preostale raspoložive energetske resurse te će dolaziti do povremenih nestašica energije, čija će cijena rasti [2].

Europska ovisnost o uvoznim fosilnim gorivima postaje prijetnja gospodarskoj stabilnosti. Zbog toga je vrlo važno da Europa razvija vlastite resurse na bazi obnovljivih izvora energije i maksimalno promovira energetska učinkovitost.

3 PROIZVODNJA ELEKTRIČNE ENERGIJE IZ OBNOVLJIVIH IZVORA ENERGIJE

Europska komisija je već 2000. godine u dokumentu pod nazivom Zelena knjiga o sigurnosti opskrbe energijom (COM 2000 769 final), upozorila da Europska unija ima strukturalne slabosti glede energetske opskrbe i da mora preuzeti odgovornost za svoju energetska sudbinu [3].

Smjernicom 2001/77EC o promidžbi uporabe električne energije proizvedene iz obnovljivih izvora energije na unutarnjem tržištu električne energije daje se naglasak na promociju električne energije iz obnovljivih izvora energije. Zahtijeva se pojednostavljenje nacionalnih administrativnih procedura za ishođenje suglasnosti i dozvola za izgradnju objekata na bazi obnovljivih izvora energije [4].

U dokumentu nazvanom Zelena knjiga o europskoj strategiji održive, konkurentne i sigurne opskrbe energijom – (COM 2006 105 final), utvrđena je buduća uloga obnovljivih izvora energije i energetske učinkovitosti [5].

ing the security of system operation, i.e. the security of the electricity supply.

2 ELECTRICITY SUPPLY IN GENERAL

We live in a world in which energy consumption is rising rapidly. Europe is expecting a 30 % increase in electricity consumption by the year 2030. If European energy strategy does not change, in that year European dependence on energy imports would amount to approximately 67 % (Figure 1).

The time of a secure energy supply has passed. The days of cheap and sufficiently available energy are behind us. This century will witness competition by the world economic powers for the remaining available energy resources and there will be periodical energy shortages and rising energy prices [2].

European dependence on imported fossil fuels has become a threat to economic stability. Therefore, it is very important for Europe to develop its own resources based on renewable energy sources and the maximum promotion of energy efficiency.

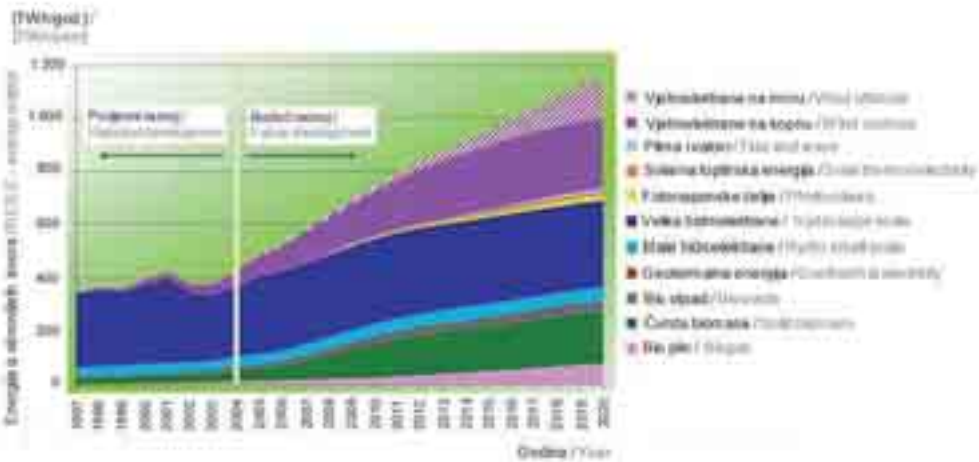
3 ELECTRICITY GENERATION FROM RENEWABLE ENERGY SOURCES

Already in the year 2000, the European Commission cautioned that the European Union has structural weaknesses regarding energy supply and must assume responsibility for its energy destiny in a document known as the Green Paper (COM 2000 769 final), [3].

Directive 2001/77EC on Promoting Electricity Produced from Renewable Energy Sources on the Internal Electricity Market requires the simplification of national administrative procedures for the authorization of the construction of facilities for the generation of electricity from renewable sources [4].

In a document known as the Green Paper, A European Strategy for Sustainable, Competitive and Secure Energy – (COM 2006 105 final), the future roles of renewable energy sources and energy efficiency are specified [5].

Energy efficiency was particularly discussed in a document entitled Action Plan for Energy Efficiency – (COM 2006 545) [6], in which the feasibility



Stika 2 – Prognozirani rast proizvodnje električne energije iz obnovljivih izvora energije do 2020. godine [7]
 Figure 2 – Projections of the growth in electricity production from renewable energy sources up to the year 2020 [7]

Energetska učinkovitost je posebno razrađena u dokumentu pod nazivom Akcijski plan za energetska učinkovitost – (COM 2006 545) [6], kojim se procjenjuje izvodljivost smanjenja potrošnje električne energije na strani potrošnje i opskrbe za 20 %. Navedeni su ključni elementi europske energetske budućnosti, koja se svodi na revoluciju u području energetske učinkovitosti i korištenje obnovljivih izvora energije.

Europska komisija je u siječnju 2007. godine objavila obvezujući dokument za zemlje članice EU, pod nazivom Plan razvoja obnovljivih izvora energije – (COM 2006 848 final), [7] u kojem se utvrđuje udio obnovljivih izvora energije u energetske miks. Cilj je da električna energija proizvedena iz obnovljivih izvora energije pokriva 20 % bruto potrošnje električne energije EU u 2020. godini. Na taj način bi se povećala sigurnost opskrbe električnom energijom i smanjila emisija stakleničkih plinova.

Procjena udjela obnovljivih izvora energije u proizvodnji električne energije u 2020. godini predočena je na slici 2.

U ožujku 2007. godine vlade i parlamenti zemalja članica Europske unije su jednoglasno prihvatile 20 postotno učešće obnovljivih izvora energije u pokrivanju potrošnje električne energije do 2020. godine

U okviru projekta EWEA udruge pod nazivom: Europska tehnološka platforma (TP Wind) [8] - koja je objavljena 2005. godine predočena je vizija korištenja energije vjetera u Europskoj uniji, po kojoj bi ona trebala pokrivati više od četvrtine potrošnje električne energije 2030. godine. Navode se prioritarna istraživanja i potrebni fi-

ity of reducing consumption and supply by 20 % is assessed. Key elements are cited regarding the future of European energy, which are revolutionary in the areas of energy efficiency and the use of renewable energy sources.

In January 2007, the European Commission published a document for the Member States of the EU entitled Renewable Energy Road Map, Renewable Energies in the 21st Century: Building a More sustainable Future – (COM 2006 848 final), [7] in which the share of renewable energy sources in the energy mix is specified. The target is for electricity generated from renewable energy sources to cover 20 % of total electricity consumption by the EU in the year 2020. In this way, the security of the electricity supply would be increased and the emission of greenhouse gasses would be decreased.

An estimate of the share of renewable energy sources in electricity production in the year 2020 is presented in Figure 2.

In March 2007, the EU heads of state unanimously agreed to a binding renewables target of 20 % by 2020.

Within the framework of a project implemented by the European Wind Energy Association (EWEA) entitled European Technology Platform for Wind (TP Wind) [8], which was published in the year 2005, a vision of the use of wind energy in the European Union was presented, according to which it should cover over a quarter of the total energy consumption in the year 2030.

This vision outlines research priorities as well as the required financial and human resources for

nancijski i ljudski resursi za ostvarenje te vizije. Platformom se predviđa da će energija vjetra 2020. godine pokrivati 12 % do 14 % bruto potrošnje električne energije Europske unije, s ukupnim proizvodnim kapacitetima u VE od 180 GW.

Očekuje se da će se proizvodnjom VE u 2030. godini pokrivati između 22 % i 28 % potrošnje električne energije, s izgrađenim proizvodnim kapacitetima u VE od 300 GW.

Projekt nazvan SUPWIND koji je pokrenut krajem 2006. godine posvećen je utvrđivanju i vrednovanju investicija u regionalne i transnacionalne prijenosne vodove i alate za upravljanje sustavom u uvjetima velikog opsega prihvatne VE u sustave pojedinih zemalja.

Projekt Prihvat vjetroenergije u europski elektroenergetski sustav (EWIS) koju je pokrenula Europska udruga operatora sustava (ETSO) početkom 2007. godine ponudio je rješenja za specifične izazove koji su se pojavili u Europi kao posljedica velikog opsega uključenosti VE u nekoliko europskih zemalja članica, a odnose se na stabilnost sustava i sigurnost opskrbe električnom energijom u Europi [9].

Projekt Tradewind u okviru programa Intelligentna energija za Europu ponudit će mjere za poboljšanje internog tržišta električne energije, u uvjetima većeg opsega zastupljenosti električne energije iz VE na tržištu.

Trenutačno postoje prepreke bržem prihvatu VE u sustave većine zemalja članica Europske unije. Rezultati Tradewind projekta, čija se završna obrada očekuje do listopada 2008. godine, koristit će se za pronalaženje učinkovitih načina za otklanjanje tih prepreka. Očekuje se izrada preporuka za osuvremenjivanje infrastrukture mreže i poboljšanje mehanizama trgovanja električnom energijom [10].

Obnovljivi izvori energije i energetska učinkovitost imaju ključnu ulogu u dokumentu Europske komisije Izvješće o energetskej strategiji Europske unije, objavljenom 2007. godine [11].

Europska komisija je objavila u siječnju 2007. godine svoju novu energetske strategiju, pod nazivom Europska energetska politika – (COM 2007 1 final) [12] poznatu kao energetske paket o internom tržištu plina i električne energije prema kojoj se zemlje članice obvezuju na:

- 20 % udjela obnovljivih izvora energije u pokrivanju potrošnje električne energije,
- vlasničko razdvajanje prijenosnih i proi-

achieving it. The platform predicts that in the year 2020 wind energy will cover 12 % to 14 % of the total electricity consumption of the European Union, with an installed wind power capacity totaling 180 GW.

It is anticipated that WPPs will generate between 22 % and 28 % of the electricity consumed in 2030, with an installed capacity of 300 GW.

A project entitled Decision Support for Large-Scale Integration of Wind Power (SUPWIND) launched in late 2006 is devoted to the determination and evaluation of regional and transnational transmission line investments and tools for system control under conditions of the large-scale integration of WPPs into the systems of individual countries.

The European Wind Integration Study (EWIS), which was launched by the European Transmission System Operators (ETSO) in early 2007, offered a solution for specific challenges that have occurred in Europe due to the large-scale integration of WPPs in several European Member States, and refer to system stability and the security of the electricity supply in Europe [9].

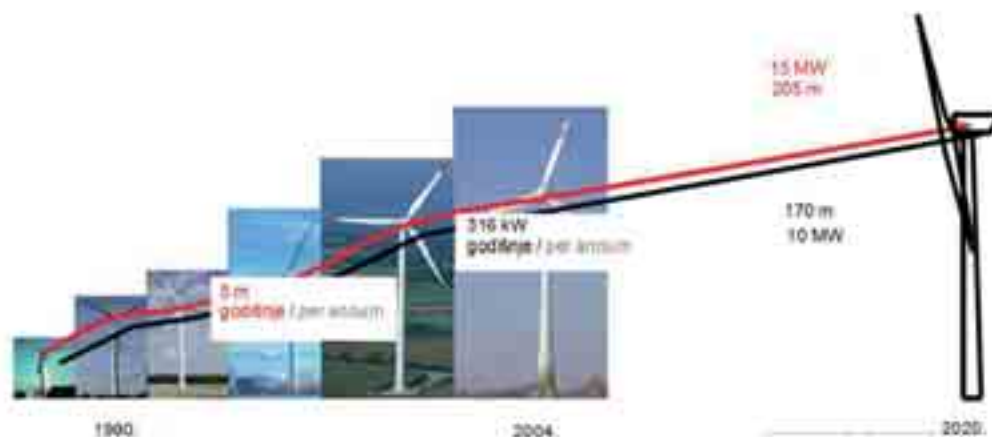
The project Tradewind within the Intelligent Energy-Europe program will offer measures for improving the internal electricity market, under conditions where there is a large share of electricity from WPPs on the market.

There are currently obstacles to the rapid integration of WPPs in the systems of the majority of the Member States of the European Union. The results of the Tradewind project, anticipated in final form by October 2008, will be used for finding efficient ways to remove these obstacles. Recommendations are anticipated for the modernizing of infrastructure networks and improving the trade mechanisms [10].

Renewable energy sources and energy efficiency have key roles in the Strategic Energy Review of the European Commission, published in the year 2007 [11].

In January 2007, the European Commission published its new energy strategy, entitled An Energy Policy for Europe – (COM 2007 1 final) [12], known as an energy package for the internal gas and electricity markets according to which the Member States undertake the following commitments:

- a 20 % share of renewable energy sources to cover electricity consumption,
- unbundling of transmission and generation activities on the electricity and gas markets,
- a priority plan for the construction of intercon-



Slika 3 – Očekivani rast jedinične snage vjetroagregata na moru [10]
 Figure 3 – Increases expected in the unit capacities of offshore wind power plants [10]

- zvodnih djelatnosti na tržištu električne energije i plina,
- prioritetni plan izgradnje interkonekcijskih vodova između sustava pojedinih zemalja članica,
- 20 %-tno smanjenje stakleničkih plinova do 2020. godine.

4 TEHNOLOŠKI RAZVOJ VE LOCIRANIH NA MORU

Početkom 70-tih godina, nakon prve naftne krize, postalo je jasno da energija vjetra može smanjiti ovisnost o fosilnim gorivima.

Zahvaljujući intenzivnim istraživačkim i razvojnim aktivnostima, prvi komercijalni vjetroagregati su se pojavili 1980. godine. Daljnji komercijalni i tehnološki razvoj bio je koncentriran na povećanje jedinične snage vjetroagregata i na smanjenje proizvodne cijene električne energije. Visina stupa vjetroagregata je povećana od početnih desetak na 126 metara, a jedinična snaga je povećana od 50 kW na 5 000 kW [13].

Nakon intenzivne izgradnje VE na kopnu dolazi vrijeme intenzivnije izgradnje VE na moru, koje će se tehnički sve više razlikovati od VE na kopnu. Manja turbulencija, manje zamaranje materijala, duži pogonski vijek, manji zahtjevi na razinu buke i jednostavnije upravljanje, samo su neki od preduvjeta koji će utjecati na izvedbu vjetroagregata, koji će se graditi na moru. Očekuje se da će se rast jediničnih snaga i dimenzija vjetroagregata na moru kretati prema slici 3 [10].

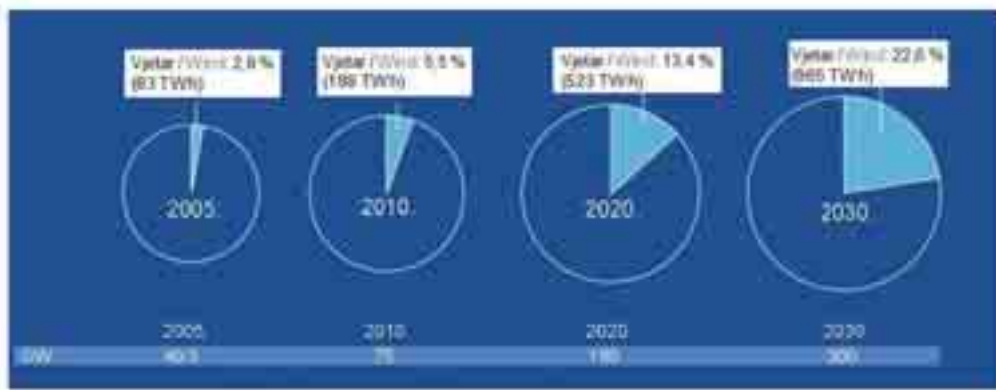
- rection lines between the systems of individual Member States,
- a 20 % reduction in greenhouse gasses by the year 2020.

4 TECHNOLOGICAL DEVELOPMENT OF OFFSHORE WPPs

In the early 1970s following the first oil crisis, it became clear that wind energy could reduce dependence upon fossil fuels.

Owing to intensive research and development activities, the first commercial wind power plants appeared in the year 1980. Further commercial and technological development was concentrated on increasing the unit capacity of wind power plants and reducing electricity generating costs. The height of the wind turbine tower was increased from the initial 10 meters to 126 meters, and the unit capacity was increased from 50 kW to 5 000 kW [13].

Following intensive construction of onshore WPPs comes a period of intense construction of offshore WPPs, which will increasingly differ technically from onshore WPPs. Lower turbulence, less material fatigue, longer operating lifetime, less rigorous noise requirements and simpler control are only some of the prerequisites that will affect the installation of offshore wind power plants. It is expected that the unit capacities and dimensions of offshore power plants will increase, as shown in Figure 3 [10].



Slika 4 – Doprinos vjetroenergije [TWh] pokrivanju potrošnje električne energije EU. Rast instalirane snage VE od 2005. do 2030. godine [15]
Figure 4 – Contribution of wind power [TWh] to covering the electricity consumption of the EU. Growth in the installed capacities of WPPs from 2005 to 2030 [15]

5 PREDUVJETI ZA PRIHVAT VELIKE KOLIČINE ELEKTRIČNE ENERGIJE IZ VE U ELEKTROENERGETSKI SUSTAV

U 2005. godini VE su proizvele više od 80 TWh električne energije ili 2,6 % godišnje potrošnje električne energije Europske unije. To je bio ekvivalent godišnje potrošnje Danske i Portugala zajedno [13].

U 2007. godini je proizvodni kapacitet VE povećan za 18 % i dosegao brojku od 56 535 MW. Taj proizvodni kapacitet će proizvoditi 119 TWh električne energije u prosječno vjetrovitoj godini, što je 3,7 % bruto potrošnje električne energije u Europi.

Trenutačno Europa raspolaže sa 60 % svjetskih proizvodnih kapaciteta u VE, koji su u svijetu dostigli razinu od 94 GW, od kojih je 20 GW instalirano u 2007. godini [14].

Zahvaljujući tom uspjehu, postavljen je novi cilj Europske komisije za 2010. godinu, proizvodnju VE od 188 TWh, odnosno pokrivanje 5,5 % bruto potrošnje električne energije Europske unije. Proizvodnja VE bi po ovom scenariju 2020. godine trebala pokrivati 13,4 %, a 2030. godine oko 22,6 % bruto potrošnje električne energije (slika 4) [15].

Europska udruga proizvođača opreme za vjetroelektrane (EWEA) je u ožujku 2008. godine objavila dokument pod nazivom Čista energija – scenariji korištenja energije vjetra do 2030. godine [16]. U dokumentu su obrađena tri razvojna scenarija VE za 2010., 2020. i 2030.

5 PREREQUISITES FOR THE INTEGRATION OF LARGE QUANTITIES OF ELECTRICITY FROM WPPs INTO AN ELECTRICAL POWER SYSTEM

In the year 2005, WPPs generated over 80 TWh of electricity or 2,6 % of the annual energy consumption of the European Union. This was the equivalent of the annual consumption of Denmark and Portugal combined [13].

In the year 2007, the generating capacity of WPPs increased to 18 % and reached a figure of 56 535 MW. This generating capacity will produce 119 TWh of electricity in a year with average wind, which is 3,7 % of the total electricity consumption in Europe.

Europe currently has 60 % of the available total generating capacity of WPPs, which in the world has reached the level of 94 GW, of which 20 GW was installed in the year 2007 [14].

Owing to this success, a new target has been established by the European Commission for the year 2010, the generation of 188 TWh by WPPs, i.e. covering 5,5 % of the total electricity consumption of the European Union. Wind power generation according to this scenario would have to cover 13,4 % in the year 2020 and approximately 22,6 % of the total electricity consumption in the year 2030 (Figure 4) [15].

In March 2008, the European Wind Energy Association (EWEA) issued a document entitled Pure Power – Wind Energy Scenarios up to 2030 [16]. The document presents three development scenarios for WPPs for the years 2010, 2020 and 2030. The effects



Slika 5 – Predviđanje proizvodnje električne energije VE u EU u 2030. [16]
Figure 5 – Forecast of electricity generated by WPPs in the EU up to the year 2030 [16]

godinu. Detaljno su analizirani učinci izgradnje VE na proizvodnju električne energije, emisiju stakleničkih plinova i gospodarstvo zemalja članica Europske unije.

Na slici 5 predočeno je predviđanje proizvodnje električne energije VE u 2030. godini [16].

EWEA, koja predstavlja industriju opreme za VE, vrlo aktivno promovira razvoj korištenja energije vjetra u Europi i svijetu. EWEA udruuga ima 500 članova iz 45 zemalja svijeta. To su proizvođači opreme za VE, dobavljači pojedinih komponenti, istraživački instituti, nacionalne udruge za vjetroenergiju i obnovljive izvore energije, developeri, opskrbljivači električnom energijom, financijska i osiguravajuća društva te konzultanti.

EWEA je objavila elaborat pod naslovom Prihvata velike količine vjetroenergije u sustav opskrbe električnom energijom (prosinac 2005.), u kojem su predočene detaljne analize tehničkih ekonomskih i pravnih pitanja, utemeljenih na 180 izvora, objavljenih podataka, izvješća, istraživačkih radova i studija radi opsežnijeg i bržeg uklapanja VE u elektroenergetski sustav [2].

U Bruxellesu je u organizaciji udruge EWEA održana krajem 2006. godine konferencija pod nazivom Europska konferencija o vjetroenergiji (EWEC 2006), na temu prihvata velikih količina električne energije proizvedene u VE u europski elektroenergetski sustav, s dvije ključne teme:

of the construction of WPPs on the production of electricity, greenhouse gas emissions and the economies of the Member States of the European Union are analyzed in detail.

In Figure 5, a forecast of electricity generated by WPPs up to the year 2030 is presented [16].

EWEA, which represents the wind energy industry, very actively promotes the development of the utilization of wind energy in Europe and the world. EWEA has 500 members from 45 countries around the world. These are manufacturers of equipment for WPPs, suppliers of individual components, research institutions, national associations for wind power and renewable energy sources, developers, electricity suppliers, financial and insurance companies, and consultants.

EWEA has issued a report entitled Large-Scale Integration of Wind Energy in the European Power Supply (December 2005), including detailed analyses of technical, economic and legal questions, based upon 180 sources, published data, reports, research investigations and studies for the purpose of more extensive and rapid integration by WPPs into the energy system [2].

A conference organized by EWEA was held in Brussels in late 2006, entitled the European Wind Energy Conference (EWEC) 2006, on the theme of the large-scale integration of electricity produced by WPPs within the European electricity system, with two key topics:

- tehnička i ekonomska integracija električne energije VE u električnu mrežu, odnosno na tržište električne energije,
- politički preduvjeti za daljnji razvoj VE na kontinentalnim i morskim lokacijama.

S tehničkog i ekonomskog aspekta, moguć je značajan doprinos energije vjetra proizvodnji električne energije u Europi. Taj se doprinos može ostvariti zadržavanjem prihvatljive razine sigurnosti sustava uz umjerene dodatne troškove. Potrebno je provesti promjene u sustavu i način upravljanja sustavom.

Prihvat VE ukupne snage od 15 % do 20 % snage postojećeg konvencionalnog proizvodnog parka u sustavu ne bi trebao iziskivati velika financijska ulaganja u pojačanje i proširenje postojeće mreže, niti predstavljati rizik za stabilnost sustava i sigurnost opskrbe električnom energijom [2].

Preduvjet za učinkovit prihvat proizvodnje VE je povećanje prijenosnih kapaciteta. Što je veća mreža, to je lakše uravnotežiti promjene proizvodnje električne energije VE.

Prijenosna mreža mogla bi postati rješenje za brži prihvat obnovljivih izvora energije u sustav, umjesto uvriježenog stajališta da je ona glavni problem i tehnička prepreka razvoju obnovljivih izvora energije. Primjena pogodnih suvremenih tehnologija za proširenje mreže omogućit će:

- izgradnju elektrana na bazi obnovljivih izvora energije na najboljim lokacijama,
- uključivanje u sustav udaljenih izvora energije,
- lakše zadovoljenje zahtjeva mrežnih pravila za:
 - upravljanje VE,
 - pomoć sustavu regulacijom napona,
 - zadovoljenje zahtjeva u svezi s promjenom frekvencije,
 - sposobnost da vjetroagregat ostane u pogonu tijekom poremećaja u mreži.

U prezentiranom članku na konferenciji EWEC 2006. pod nazivom Tehnologije prijenosa električne energije u funkciji većeg prihvata energije VE u sustav predložena je uloga prijenosne mreže koja treba biti podrška snažnom i bržem razvoju obnovljivih izvora energije [17].

U članku se obrazlažu razlozi za primjenu podzemnog prijenosa električne energije. Riječ je o raspoloživoj novoj HVDC Light

- the technical and economic integration of electricity from WPPs into the electrical power grid, i.e. on the electricity market,
- the political prerequisites for the further development of WPPs at onshore and offshore locations.

From the technical and economic aspects, a significant contribution by wind power to electricity production in Europe is feasible. This contribution can be achieved with the maintenance of an acceptable level of system security at moderate additional cost. It is necessary to make changes in the system and manner of system control.

The integration of wind power into the system in the amount of 15 % to 20 % of the power currently generated by conventional power plants should neither require major financial investments in strengthening and extending the existing grid nor pose a risk to the stability of the system or the safety of the electricity supply [2].

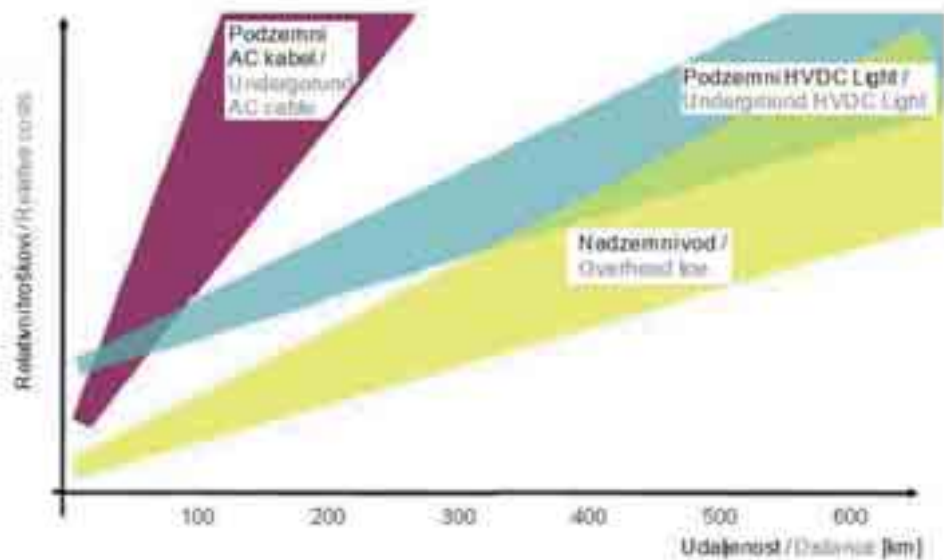
A prerequisite for the efficient integration of the production of WPPs is to increase the transmission capacities. The larger the grid, the easier it is to balance changes in electricity production by WPPs.

A transmission grid could become the solution for the rapid integration of renewable energy sources into a system, contrary to ingrained opinion that it is the main problem and technical barrier to the development of renewable energy sources. The application of suitable modern technologies for grid extension will facilitate the following:

- the construction of power plants based on renewable energy sources in the optimal locations,
- integration into the system of distant energy sources,
- facilitated compliance with the requirements of grid codes for the following:
 - WPP control,
 - support for the voltage regulation system,
 - compliance with requirements regarding frequency variation,
 - the ability of a wind power plant to remain in operation during grid disturbances.

In an article presented at EWEC 2006 entitled Transmission Technologies to Support Integration of Wind Power Technology, the role of the transmission grid is presented, which should be to provide support for the strong and rapid development of renewable energy sources [17].

In the article, reasons are explained for the underground transmission of electricity. This concerns a newly available HVDC light alternative



Slika 6 – Relativni troškovi prijenosa električne energije [17]
 Figure 6 – Relative costs of electricity transmission [17]

alternativi, za udaljenosti prijenosa energije preko 500 km, drastičnom smanjenju troškova i skraćenju vremena potrebnog za lociranje mjesta kvara i popravka kabela [17].

for transmitting electricity over 500 km, drastic reduction in costs and a reduction in the time required for locating a fault site and cable repair [17].

Posebno se ističe sve manja naklonost javnosti izgradnji nadzemnih vodova, dugotrajno ishođenje dozvola i suglasnosti te povećani ekološki zahtjevi za nadzemne vodove (slika 6).

It particularly emphasizes decreasing public approval for the construction of overhead lines, the long-term issue of permits and authorizations, and increased ecological requirements for overhead lines (Figure 6).

Infrastrukturu mreže treba poboljšavati na nacionalnoj, regionalnoj i europskoj razini. Poboljšanje mreže može se ostvariti na kratkoročnoj i dugoročnoj vremenskoj osnovi. Kratkoročno je moguće provesti

The grid infrastructure should be improved on the national, regional and European levels. Improving the grid can be achieved on a short-term and long-term basis. In the short-term, it is possible to optimize the grid, install flexible alternative cur-



Slika 7 – Shematski prikaz potencijalnih trasa interkontinentalnog prijenosnog sustava [17]
 Figure 7 – Potential routes of the intercontinental transmission system [17]



Slika 8 – Vizija visokonaponske super mreže za prijenos energije VE na moru u Europu [17]
Figure 8 – Vision of a high voltage supergrid for the transmission of energy generated by offshore WPPs [17]

optimizaciju mreže, ugraditi FACTS uređaje i provesti tzv. blage mjere.

Na dugoročnoj osnovi računa se s izgradnjom europske interkontinentalne super mreže (slika 7) [17].

Izgradnjom europske super mreže za prijenos električne energije VE lociranih na moru (slika 8), znatno bi se ublažio učinak promjenljivosti proizvodnje VE na širokom europskom prostoru, bilo bi moguće točnije prognozirati kratkoročnu proizvodnju VE, poboljšalo bi se funkcioniranje internog tržišta električne energije i prekogranična razmjena energije [17].

6 UTJECAJ PRIHVATA PROMJENLJIVE PROIZVODNJE VE NA KARAKTERISTIKE I TROŠKOVE ELEKTROENERGETSKOG SUSTAVA

Europa je svjetski predvodnik u razvoju i korištenju obnovljivih izvora energije, od kojih energija vjetrova najviše obećava. Od 2000. godine proizvodni kapaciteti u VE su povećani za više od 150 % [13].

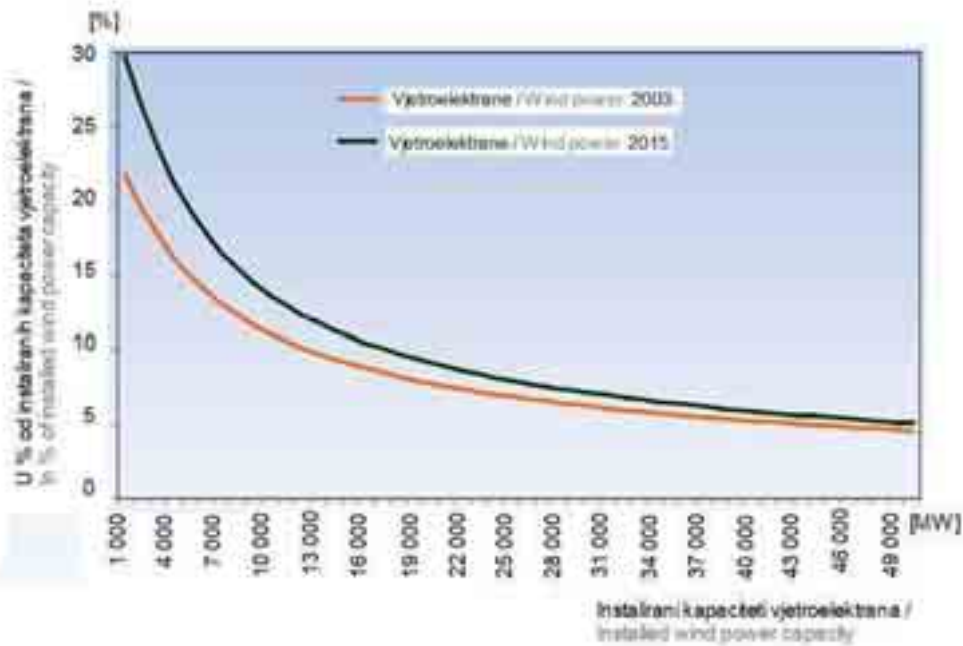
rent transmission systems (FACTS) and implement moderate measures.

On the long-term basis, hopes are riding on the construction of the European intercontinental supergrid (Figure 7) [17].

With the construction of the European supergrid for the transmission of electricity from offshore WPPs (Figure 8), the impact of the variability of the WPP production throughout Europe would be lessened, it would be possible to forecast short-term WPP production more accurately, and the function of the internal electricity market and transborder energy exchanges would be improved [17].

6 THE IMPACT OF THE INTEGRATION OF VARIABLE PRODUCTION OF WIND POWER PLANTS ON THE CHARACTERISTICS AND COSTS OF AN ELECTRICAL POWER SYSTEM

Europe is a world leader in the development and use of renewable energy sources, of which wind energy is the most promising. Since the year 2000, the generating capacities of WPPs have increased by more than 150 % [13].



Slika 9 – Ovisnost snaga VE s kojom operator sustava može računati u sustavu o instaliranim kapacitetima VE [14]
 Figure 9 - The capacity credit of WPPs that a system operator can count on in a system depending on the installed wind power capacities [14]

Proizvodnjom VE ostvaruje se diversifikacija proizvodnog miksa i povećava udio proizvodnje iz domaćih resursa oslobođenih od svih rizika koji prate opskrbu fosilnim gorivima sa svjetskog tržišta.

Izgradnjom VE zamjenjuje se dio proizvodnje konvencionalnih elektrana. Snaga VE, s kojom operator sustava može računati u sustavu se kreće između 35 % i 10 % instaliranog kapaciteta VE (slika 9) [14].

Ako je u sustavu instalirano nekoliko GW, snaga VE s kojom operator sustava može računati u sustavu iznosi oko 30 %. Pri razini uključenosti od 20 GW, snaga VE s kojom operator sustava može računati u sustavu se kreće od 10 % do 15 % ukupno instalirane snage VE [14].

Utjecaj VE na sustav ovisi o razini uključenosti VE u sustavu i njegovim obilježjima. Veliki sustavi raspolazu fleksibilnim mehanizmima, koji lakše podržavaju prihvat promjenljive proizvodnje VE.

Prilagodba sustava na sve veći opseg uključenosti VE će utjecati na njegove karakteristike.

Ključno je pitanje kako uskladiti i uravnotežiti proizvodnju i potrošnju energije u sustavu s većim opsegom uključenosti VE. Rješenja su osiguranje rezervne snage u konvencionalnim elektranama, što učinkovitije predviđanje proizvodnje VE, što bolje interkonekcije sa susjed-

Wind power generation achieves diversification of the production mix and increases the share of production from domestic resources, without all the risks that accompany the fossil fuel supplied from the world market.

With the construction of WPPs, part of the production from conventional power plants is replaced. The capacity credit of WPPs that the system operator can count on in a system ranges between 35 % and 10 % of the installed wind power capacity (Figure 9) [14].

If several GW are installed in a system, the capacity credit of wind power that a system operator can count on in the system is approximately 30 %. At a level of integration of 20 GW, the capacity credit of wind power that the system operator can count on in the system ranges from 10 % to 15 % of the total installed wind power capacity [14].

The impact of WPPs on a system depends on the level of the integration of wind power into the system and its characteristics. Large systems have flexible mechanisms that can more easily support the integration of the variable production of WPPs.

The adaptation of a system to an increasing range of the integration of WPPs will affect its characteristics.

A key question is how to coordinate and balance production and energy consumption in a system with large-scale integration of WPPs. The solutions

nim sustavima, upravljanje potrošnjom i skladištenje energije [2].

Postojeći modeli upravljanja sustavom i raspoloživa pričuvna snaga u sustavu, namijenjena za uravnoteženje svakodnevnih promjena potrošnje i opskrbe je dostatna za uravnoteženje dodatne promjenljive električne energije proizvedene u VE, pri njihovoj razini uključenosti do 20 % bruto potrošnje sustava [2].

U Danskoj su VE već 2004. godine pokrivala 21 % bruto potrošnje električne energije. U danskom zapadnom prijenosnom sustavu, koji nije bio priključen na istočni dio zemlje, četvrtina potrošnje tog dijela Danske pokrivena je proizvodnjom VE u godini s prosječnim intenzitetom vjetra. U nekim slučajevima je vjetar mogao pokrivati 100 % potrošnju električne energije.

Veći opseg prihvata VE u sustav je često porican kao nemoguć i mnogi su operatori sustava bili neskloni promjenama davno uspostavljenih procedura zbog uključivanja proizvodnje VE u sustav.

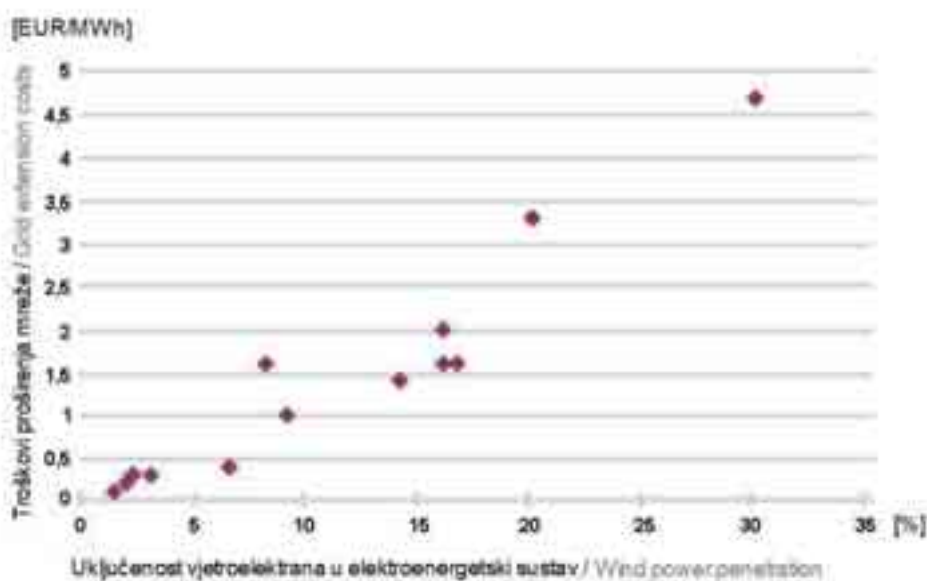
Operatori danskog sustava su u početnoj fazi bili skeptični glede veličine snage VE koja bi se mogla uključiti u sustav. U tijeku tri godine od 1999. kapacitet VE u Jutland Fyn sustavu se povećao sa 1 100 MW na 2 400 MW. Sedam ili osam godina ranije operatori su smatrali da sustav neće funkcionirati ako se snaga VE povećá iznad 500 MW.

are to secure reserve power in conventional power plants, efficient forecasting of WPP generation, optimal interconnections with neighboring systems, consumption control and energy storage [2].

Existing models of system control and available reserve power intended for the balancing of daily variations in supply and demand are sufficient for balancing additional variations in the electricity generated by WPPs at a level of integration of up to 20 % of total system consumption [2].

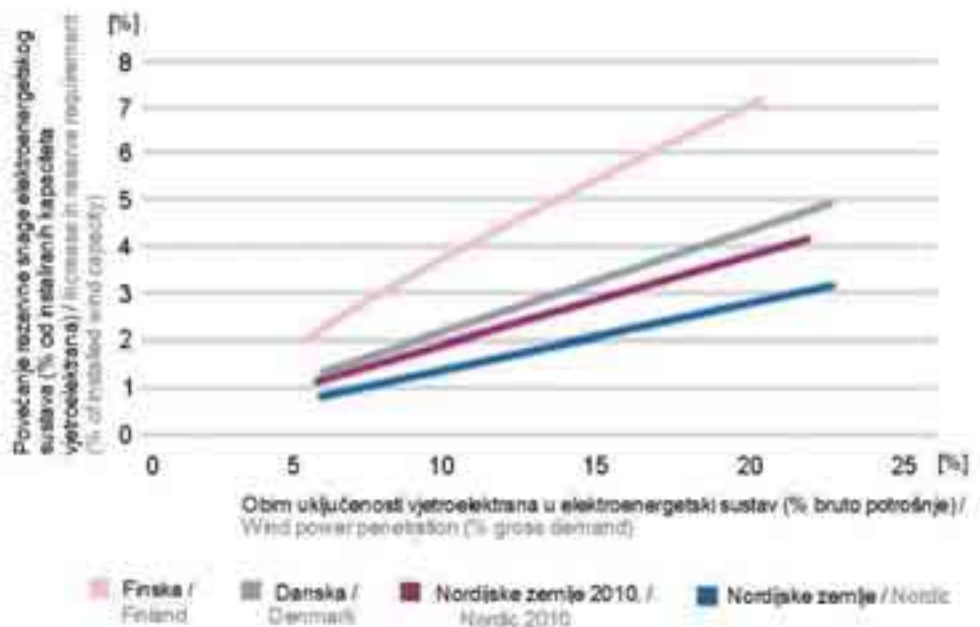
In the year 2004, WPPs already covered 21 % of the total electricity consumption in Denmark. In the western Danish transmission system, which was not connected to the eastern part of the country, a quarter of the consumption of that part of Denmark is covered by wind power generation in a year with average wind intensity. In some cases, wind could cover 100 % of electricity consumption. Greater integration of WPPs into a system is frequently considered to be impossible and many system operators have opposed changes in long-established procedures due to the integration of wind power generation into a system.

In the initial phase, the operators of the Danish system were skeptical regarding the amount of power from WPPs which could be integrated into the system. During three years, starting in 1999, the capacity of the wind power plant in the Jutland Fyn system increased from 1 100 MW to 2 400 MW. Seven or eight years earlier, the operators had believed that the system would not function if the wind power from WPPs were to increase to over 500 MW.



Slika 10 – Dodatni troškovi proširenja mreže u ovisnosti o razini uključenosti VE u sustav [2]

Figure 10 – Additional costs of grid extension as a function of the level of the integration of WPPs into a system. [2]



Slika 11 – Ovisnost pričuvne snage sustava o opsegu uključenosti VE [2]
 Figure 11 – The dependence of the reserve power of a system on wind power penetration [2]

6.1 Troškovi prihvata VE u sustav [15]

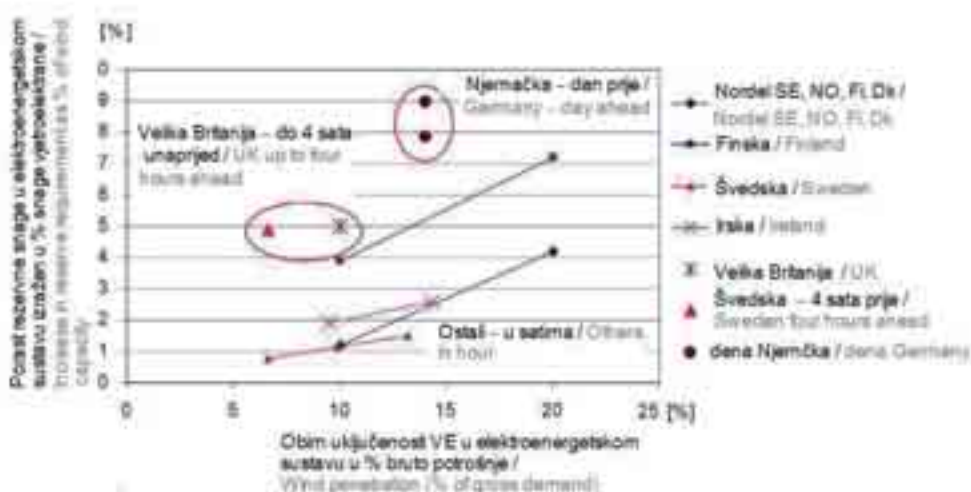
Dodatni troškovi proširenja mreže ovise o razini uključenosti VE u sustav. Oni iznose od 0,1 EUR/MWh do 4,7 EUR/MWh proizvedene električne energije VE (slika 10).

Ovisnost pričuvne snage sustava o opsegu uključenosti VE na nordijskom području predložena je na slici 11.

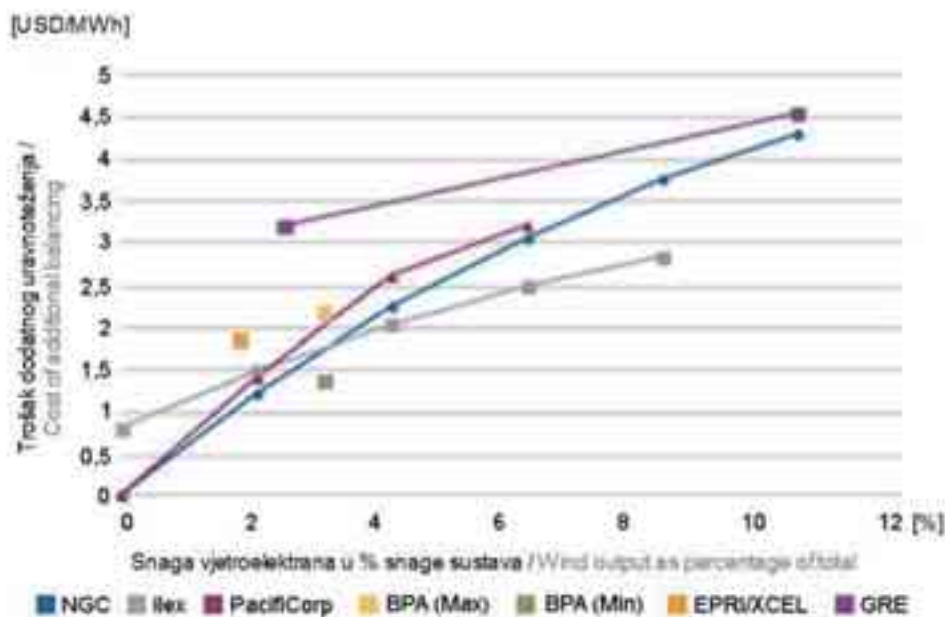
6.1 Costs of integrating WPPs into a system [15]

Additional costs of grid extension depend upon the level of the integration of WPPs into a system. These range from 0,1 EUR/MWh to 4,7 EUR/MWh of electricity produced by WPPs (Figure 10).

The dependence of the reserve power of a system on wind power penetration in the Nordic region is presented in Figure 11.



Slika 12 – Pričuvna snaga sustava u ovisnosti o opsegu uključenosti VE u sustavu i procjenama proizvodnje VE unaprijed [18]
 Figure 12 – The dependence of the reserve power of a system on the wind power penetration in the system and the estimated forecasts of wind power generation [18]



Slika 13 – Procjena dodatnih troškova uravnoteženja na temelju šest obrađenih studija [2]
Figure 13 – Estimate of additional balancing costs based upon six studies [2]

Ovisnost pričuvne snage sustava o opsegu uključenosti VE u sustavu i procjenama proizvodnje VE unaprijed predočena je na slici 12.

Dodatni troškovi uravnoteženja sustava, za razinu uključenosti VE do 10 % instalirane snage sustava iznose od 1 EUR/MWh do 3 EUR/MWh proizvedene električne energije VE u sustavu, a za razinu uključenosti VE do 20 % instalirane snage sustava iznose od 2 EUR/MWh do 4 EUR/MWh proizvedene električne energije VE u sustavu.

Procjena dodatnih troškova uravnoteženja na temelju šest obrađenih studija predočena je na slici 13.

Troškovi priključenja VE na prijenosnu mrežu iznose od 0 EUR/MWh do 4 EUR/MWh proizvedene električne energije VE.

Cijena električne energije kod krajnjeg potrošača povećava se za manje od 5 %.

7 MREŽNA PRAVILA ZA VE

Mrežna pravila za VE trebaju odražavati stvarne tehničke potrebe pogona sustava. Koncipiranje mrežnih pravila trebalo bi se ostvarivati u neposrednoj suradnji operatora sustava, sektora vjetroenergije, energetskih regulatora i nadležnih državnih institucija.

Sadašnja mrežna pravila često sadrže skupe i izazovne zahtjeve tamo gdje za to nema tehnič-

The dependence of the reserve power of a system on wind power penetration in the system and estimated forecasts of wind power generation are presented in Figure 12.

Additional costs of system balancing at the level of wind power integration of up to 10 % of the installed system capacity are from 1 EUR/MWh to 3 EUR/MWh for the electricity generated by wind power in the system, and at the level of wind power integration of up to 20 % of the installed system capacity are from 2 EUR/MWh to 4 EUR/MWh for the electricity generated by wind power in the system.

An estimate of additional balancing costs based upon six studies is presented in Figure 13.

The costs of the connection of WPPs to a transmission grid are from 0 EUR/MWh to 4 EUR/MWh for the electricity generated by wind power.

The price of electricity for the final consumer is increased by less than 5 %.

7 GRID CODES FOR WPPs

Grid codes for WPPs should reflect the actual technical requirements of system operation. Grid codes should be developed through the direct cooperation of the system operator, wind power sector, energy regulators and state institutions.

Current grid codes frequently contain expensive and challenging requirements, which lack technical justi-

kog opravdanja, zbog niske razine uključenosti VE u sustavu, što je slučaj u većini europskih zemalja [2].

Ciljevi tehničkih kriterija i zahtjeva reguliranih mrežnim pravilima su sljedeći:

- očuvanje bitnih karakteristika elektroenergetskog sustava, kao što su sigurnost pogona i kvaliteta električne energije,
- korištenje nekih svojstava VE koje su u funkciji sigurnosti pogona sustava,
- poticanje razvoja onih osobina VE koje pridonose kompatibilnosti VE i EES-a,
- omogućavanje što većeg prihvaća VE u EES, poboljšanjem integracijskih svojstava VE,
- izgradnja velikih VE koje imaju istovjetne karakteristike poput konvencionalnih elektrana.

Industrija opreme za VE nastoji što prije ispuniti tražene zahtjeve. To se prvenstveno odnosi na:

- kvalitetu električne energije, prema IEC standardima,
- primjenu SCADA sustava,
- razvoj konvertora pune snage za promjenljivu brzinu vrtnje turbine s DFIG generatorom,
- sposobnost zadržavanja VE u pogonu tijekom poremećaja u mreži,
- pouzdano upravljanje i zaštitne funkcije vjetroagregata, odnosno VE,
- sposobnost upravljanja snagom VE tijekom poremećaja u mreži,
- sposobnost razmjene jalove energije na mjestu priključka VE na mrežu,
- registraciju odziva VE na poremećaje u sustavu,
- brzinu odziva VE na poremećaje u mreži.

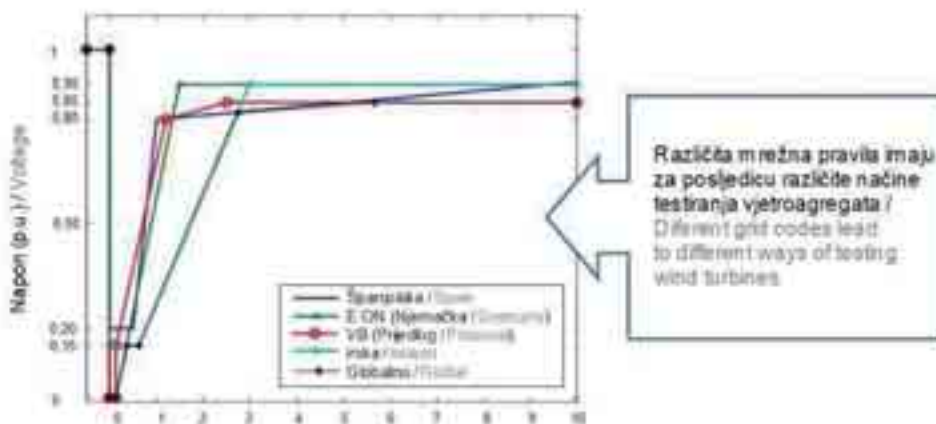
fication due to the low level of the integration of WPPs into a system, as is the case in the majority of European countries [2].

The goals of the technical criteria and requirements regulated by grid codes are as follows:

- preservation of the essential characteristics of the electricity system, such as operation security and electricity quality,
- the use of some properties of WPPs in the function of the operation security of the system,
- facilitate the maximum integration of WPPs into an electrical power system, improvement in the integrative properties of WPPs,
- construction of large WPPs with characteristics equivalent to those of conventional power plants.

The wind power equipment industry is attempting to meet these requirements as soon as possible, primarily in reference to the following:

- electricity quality, according to IEC standards,
- application of the SCADA system,
- development of full-power converters for variable speed wind turbines with DFIG generators,
- the capability of WPPs to operate during grid disturbances,
- reliable control and protective functions of wind turbines, i.e. WPPs,
- the capability of controlling the power of WPPs during grid disturbances,
- reactive power capability at the connection point of the WPP to the grid,
- recording of the response by a WPP to a system disturbance,
- the response time of a WPP to a system disturbance.



Slika 14 – Različiti zahtjevi navedeni u pet mrežnih pravila za isti poremećaj u mreži [19]
Figure 14 – Various requirements specified by five grid codes for the same grid disturbance [19]

Potrebna su jasna pravila koja jamče siguran pogon sustava. No, ta se pravila često mijenjaju, bez bilo kakve uključenosti proizvođača opreme i drugih zainteresiranih subjekata.

Operatori sustava i ostali zainteresirani partneri trebaju razvijati realistična mrežna pravila utemeljena na suvremenoj i fizički ostvarivoj tehnologiji.

Mrežna pravila i tehnički zahtjevi se uvelike razlikuju od zemlje do zemlje (slika 14). To se prvenstveno opravdava različitim razinom uključenosti VE, veličinom i karakteristikama sustava i lokalnom tradicionalnom praksom [19].

Postoje i zajednički zahtjevi gotovo svih operatora sustava, a to su:

- razmjena pogonskih podataka između operatora sustava i VE,
- neprekidan pogon VE u relativno širokom rasponu promjena napona i frekvencije,
- regulacija djelatne snage i frekvencije,
- regulacija jalove snage i napona.

Do neke mjere je opravdano usklađivanje različitih zahtjeva u mrežnim pravilima. Tako bi npr. usklađivanje metodologije pravodobne procjene podobnosti lokacije olakšalo proceduru priključivanja VE na mrežu.

Mrežna pravila bi zapravo trebala omogućiti veliku razinu uključenosti VE u sustav. Ona moraju smanjiti rizike vezane uz stabilnost mreže te su važna za razvoj VE, koje moraju pridonijeti stabilnom pogonu sustava.

7.1 Mrežna pravila pojedinih zemalja [20]

Španjolska

U Španjolskoj postoje opća mrežna pravila za sve nove proizvodne objekte i posebna mrežna pravila za prihvat VE u elektroenergetski sustav.

Cilj mrežnih pravila za VE je rješavanje poteškoća koje se pojavljuju u sustavu uključivanjem većeg opsega VE u sustav (15 145 MW, krajem 2007. godine).

Prema mrežnim pravilima VE moraju zadovoljiti sljedeće zahtjeve:

- trajno zadovoljavati zadane uvjete glede održavanja razine napona i frekvencije,
- zadovoljavati zadane uvjete vezane uz kvalitetu električne energije,
- ostati na mreži pri sniženju napona uzrokovano poremećajima u mreži.

Clear regulations are needed that guarantee secure system operation. However, these regulations change frequently, without any participation by equipment manufacturers and other interested parties.

System operators and other interested parties should develop realistic grid codes, based upon modern and physically feasible technology.

Grid regulations and technical requirements always differ from country to country (Figure 14). This is primarily justified by the various levels of WPP integration, size, system characteristics and traditional local practices [19].

There are also common requirements for nearly all system operators, as follows:

- exchange of operational data between the system operator and a WPP,
- continuous operation of a WPP within a relatively broad range of voltage and frequency variations,
- regulation of active power and frequency,
- regulation of reactive power and voltage.

To a certain extent, the coordination of various requirements in grid codes is justified. Thus, for example, the coordination of the methodology of the timely assessment of the suitability of a locality would facilitate the procedure for the connection of a WPP to the grid.

Grid codes should actually facilitate a high level of integration of WPPs into a system. They should reduce the risks connected with grid stability and are important for the development of WPPs, which should contribute to stable system operation.

7.1 The grid codes of individual countries [20]

Spain

In Spain there are general grid codes for all new generating facilities and separate grid codes for the integration of WPPs into the electrical power system.

The goal of the grid codes for WPPs is to resolve the difficulties that occur in a system with the integration of large-scale WPPs (15 145 MW, late 2007).

According to the grid codes, WPPs must meet the following requirements:

- continuously meet the given prerequisites regarding the maintenance of the voltage and frequency levels,
- meet the given requirements in connection with electricity quality,
- remain on the grid during reductions in voltage due to grid disturbances.

Portugal

Nova mrežna pravila reguliraju:

- sposobnost zadržavanja VE u pogonu tijekom poremećaja u mreži,
- regulaciju frekvencije,
- regulaciju napona,
- regulaciju djelatne snage,
- modeliranje VE.

Francuska, Italija, Austrija, Slovačka

Nema posebnih zahtjeva.

Nizozemska

Nema posebnih zahtjeva. Ako VE ne može ispuniti zahtjeve regulirane mrežnim pravilima, mora se zatražiti dozvola od operatora sustava za odstupanje od mrežnih pravila.

Belgija

Trenutačno nema posebnih zahtjeva izvan standardnih zahtjeva za sve elektrane. Različita pravila vrijede za manje elektrane, do 25 MW i za one veće snage. S obzirom na gustoću naseljenosti u Belgiji na kopnu nema VE većih od 25 MW. Za VE na moru primjenjivat će se njemačka mrežna pravila ili pravila ostalih zemalja.

Njemačka

Osnovni tehnički zahtjevi za priključak elektrana su utvrđeni u Mrežnim pravilima njemačkog operatora VDN. Zbog snažnog rasta elektrana na bazi obnovljivih izvora energije, zahtjevi su utvrđeni u Priručniku iz kolovoza 2004. godine. Svaki operator prijenosnog sustava je objavio vlastita mrežna pravila za priključenje na mrežu koja više ili manje slijede usvojene temeljne zahtjeve.

Grčka

U grčkim mrežnim pravilima uključen je ($n-1$) kriterij, kratkospojni omjer, granice promjene napona u priključnom čvorištu VE na prijenosnu mrežu i standardi kvalitete električne energije.

Poljska

Tehnički zahtjevi za VE sadrže: regulaciju djelatne snage, pogon pri raznim razinama napona i frekvencije, uključivanje i isključivanje iz mreže, upravljanje naponom i jalovom snagom, uvjete pogona pri poremećajima u mreži, standarde kvalitete električne energije, zaštitu, monitoring, telekomunikacijske veze i testiranje postrojenja.

Češka republika

Posebni zahtjevi u mrežnim pravilima se odnose na: minimalni raspon frekvencije i napona

Portugal

The new grid codes regulate the following:

- the ability to maintain WPPs in operation during grid disturbances,
- voltage regulation,
- active power regulation,
- modeling WPPs.

France, Italy, Austria and Slovakia

There are no special requirements.

The Netherlands

There are no special requirements. If a WPP cannot meet the requirements stipulated by the grid codes, it is necessary to seek a permit from the system operator for deviation from the grid codes.

Belgium

Currently, there are no special requirements outside the standard requirements for all power plants. Different regulations apply for small power plants, up to 25 MW and for those with a higher power rating. Due to the population density of Belgium, there are no onshore WPPs larger than 25 MW. For offshore WPPs, the German grid codes or codes of other countries will be applied.

Germany

The basic technical requirements for the connection of power plants are specified in the grid codes of the German operator VDN. Due to strong growth in power plants using renewable energy sources, the requirements are specified in a manual issued in August 2004. Each operator of a transmission system has issued a grid code for connection to the grid, which more or less follows the basic adopted requirements.

Greece

The Greek grid codes include ($n-1$) criterion, short-circuit ratio, limits of voltage variation in the connection node of a WPP to a transmission grid and standards for electricity quality.

Poland

The technical requirements for a WPP contain regulation of the active power, operation under variable levels of voltage and frequency, connection and disconnection from the grid, control of voltage and reactive power, operating conditions during grid disturbances, standards for electricity quality, protection, monitoring, telecommunications connections and equipment testing.

The Czech Republic

Special requirements in the grid codes refer to the minimum ranges of frequency and voltage for the operation of WPPs, the possibilities for reducing power, the maximum permitted power increase and regula-

za pogon vjetrogeneratora, mogućnosti smanjenja snage, maksimalno dozvoljeno povećanje snage, pravila za ponašanje generatora u različitim situacijama u sustavu (kratki spoj, regulacija napona i jalove snage, promjene frekvencije, zaštite i standardi kvalitete električne energije).

Švedska

Postoje različiti zahtjevi za razne veličine VE; velike, preko 100 MW, srednje, od 25 MW do 100 MW i male, od 1,5 MW do 25 MW. Također, postoje i zahtjevi za sposobnost zadržavanja VE u pogonu tijekom poremećaja u mreži, upravljanje naponom, upravljanje djelatnom snagom i komunikacije.

Finska

U Finskoj još ne postoje nacionalna mrežna pravila. Pripremaju se zajednička mrežna pravila na razini Udruge operatora prijenosnih sustava NORDEL-a.

Danska

Na snazi su mrežna pravila za vjetroagregate priključene na mrežu napona ispod 100 kV i za VE priključene na naponsku razinu iznad 100 kV.

Velika Britanija

Mrežna pravila Velike Britanije su novelirana 1. lipnja 2005. s dodanim zahtjevima za nove proizvodne objekte i objekte na bazi obnovljivih izvora energije, za VE i HVDC konvertore. U pravilima su navedeni sljedeći zahtjevi:

- raspon regulacije jalove energije: faktor snage od 0,95 ind. do 0,95 kap. na mjestu priključka VE na prijenosnu mrežu,
- sposobnost regulacije frekvencije na razini VE (pružanje usluga sustavu je predmet komercijalnog ugovora),
- sposobnost regulacije napona na mjestu priključka VE na prijenosnu mrežu,
- sposobnost zadržavanja VE u pogonu tijekom poremećaja u mreži: VE mora ostati na mreži tijekom trolejnog kratkog spoja u 400 kV ili 275 kV mreži u trajanju do 140 ms,
- za duže trajanje poremećaja od 140 ms, VE mora zadovoljiti zahtjeve prema zadanoj krivulji promjene napona.

Hrvatska

U Republici Hrvatskoj su na snazi Mrežna pravila za konvencionalne elektrane, kojima će se dodati tehnički zahtjevi, odnosno mrežna pravila za priključak i pogon VE na prijenosnoj mreži, o kojim se trenutačno raspravlja na stručnim i nadležnim državnim tijelima i institucijama.

tions for generator behavior under various situations in the system (short circuit, regulation of voltage and reactive power, frequency variations, protection and standards for electricity quality).

Sweden

There are different requirements for various sizes of WPPs: large, over 100 MW; average, from 25 MW to 100 MW; and small, from 1,5 MW to 25 MW. Furthermore, there are also requirements for the capability of maintaining WPPs in operation during grid disturbances, voltage control, active power control and communication.

Finland

In Finland, there are still no national grid codes. Joint grid codes are being prepared at the level of the NORDEL Transmission System Operators Association.

Denmark

Grid codes are in force for wind turbines connected to grids with voltage levels below 100 kV and for WPPs connected to grids with voltage levels above 100 kV.

Great Britain

The grid codes of Great Britain were revised on June 1, 2005, with additional requirements for new generation facilities and facilities based on renewable energy sources, WPPs and HVDC converters. The following requirements are stipulated in the codes:

- the range of the regulation of reactive power: power factor from 0,95 ind. to 0,95 cap. at the site of the WPP connection to the transmission grid,
- capability of frequency regulation at the WPP level (providing services to the system is the subject of a commercial contract),
- capability of voltage regulation at the connection point of a WPP to the transmission grid,
- capability of maintaining a WPP in operation during grid disturbances. The WPP must remain on the grid during a three-pole short circuit in a 400 kV or 275 kV grid for a duration of up to 140 ms,
- for disturbances lasting longer than 140 ms, a WPP must meet the requirements according to the specified voltage variation curve.

Croatia

In the Republic of Croatia, grid codes for conventional power plants are in force, to which will be added technical requirements, i.e. grid codes for the connection and operation of WPPs in the transmission grid, which the authorized state bodies and institutions are currently discussing.

Grid codes for WPPs also regulate technical requirements:

Mrežnim pravilima za VE se između ostalog reguliraju i tehnički zahtjevi:

- s obzirom na regulaciju frekvencije i djelatne snage,
- s obzirom na regulaciju napona i jalove snage,
- na sposobnost VE u svezi s prolaskom kroz stanje kvara u mreži.

Pravilima se propisuju karakteristike 110 kV postrojenja za priključak VE na prijenosnu mrežu, te potrebni podaci o VE u postupku prijave za priključak, probni i redovni pogon VE.

8 ISKUSTVA POJEDINIH EUROPSKIH ZEMALJA U KORIŠTENJU ENERGIJE VJETRA ZA PROIZVODNJU ELEKTRIČNE ENERGIJE

8.1 Španjolski primjer [19]

U španjolskom elektroenergetskom sustavu je do kraja 2006. godine bilo priključeno 11 000 MW VE, odnosno 20 % godišnje bruto potrošnje električne energije. Povremeno i u kratkim razdobljima su VE pokrivali i 30 % potrošnje bez većih problema u sustavu.

U Španjolskoj je u 2007. godini izgrađeno i priključeno na mrežu 3 522 MW novih VE, najviše

- the regulation of frequency and active power,
- the regulation of voltage reactive power,
- the capability of WPPs to remain in operation during grid disturbances.

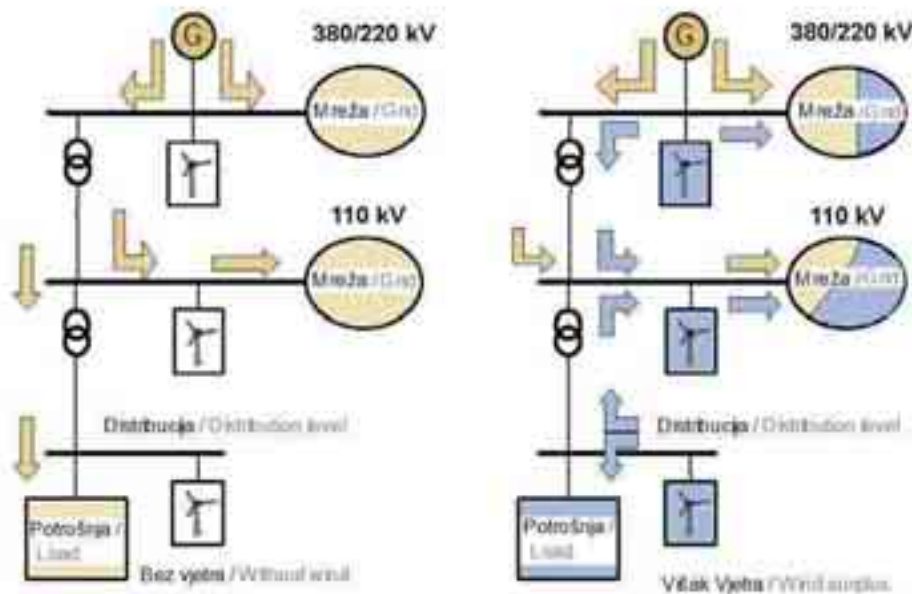
Codes specify the characteristics of a 110 kV substation for the connection of a WPP to the transmission grid, data required on the WPP for the registration of the connection, trial period and regular operation of the WPP.

It may be said in conclusion that in every country grid codes for WPPs must express the specific problems of the integration of WPPs into the system, depending on the level of WPP integration, structure and size of the system, and the number of interconnection lines with the systems of neighboring countries.

8 EXPERIENCES OF INDIVIDUAL EUROPEAN COUNTRIES IN THE USE OF WIND ENERGY FOR THE PRODUCTION OF ELECTRICITY

8.1 The Spanish example [19]

In the Spanish electrical power system, 1 100 MW of wind power was connected to the electrical power system in late 2006, i.e. 20 % of the total annual electricity consumption. Occasionally and for short periods, WPPs covered 30 % of consumption without



Slika 15 – Tokovi energije bez VE i s VE u sustavu [19]
Figure 15 – Energy flows with and without WPPs in the system [19]

od svih zemalja članica EU27 (41,2 % ukupnog porasta instalirane snage VE EU u 2007. godini).

Krajem 2007. godine ukupno instalirani proizvodni park VE u Španjolskoj iznosio je 15 145 MW.

Ranije je proizvodnja električne energije u VE utjecala na upravljanje potrošnjom i neznatno na pogon sustava. S vremenom su se stvari znatno promijenile, naročito s većim opsegom uključenosti VE u sustav. Sve se više VE priključuje i na 380/220 kV prijenosni sustav. Napon i tokovi energije i snage postaju sve značajniji i oni moraju biti pod stalnim nadzorom operatora sustava (slika 15).

Ispad velikog broja VE izazvan smetnjama i kvarovima u prijenosnoj mreži utječe na stabilnost mreže. VE su obično daleko od centara potrošnje, a to je uvelike utjecalo na proširenje električne mreže.

Zahtjevi za angažiranjem dodatne pričuvne energije zbog promjenjive proizvodnje VE su manji od očekivanih. Rezultati primjene modela prognoziranja su sve povoljniji i proizvodnja VE na širem geografskom prostoru smanjuje odstupanje od plana.

Zakon 54/97 utvrđuje razdvajanje poslovanja elektroprivrednih poduzeća, uz zadržavanje vlasništva nad sredstvima proizvodnje. Elektroprivredna poduzeća igraju važnu ulogu u španjolskom sektoru vjetroenergije. Elektroprivredna poduzeća su operatori elektrana i vlasnici 60 % španjolskog proizvodnog parka.

major problems in the system.

In the year 2007, WPPs generating 3 522 MW were constructed and connected to the grid, the most of all the Member States of the EU27 (41,2 % of the total increase in the installed capacity of WPPs of the EU in the year 2007).

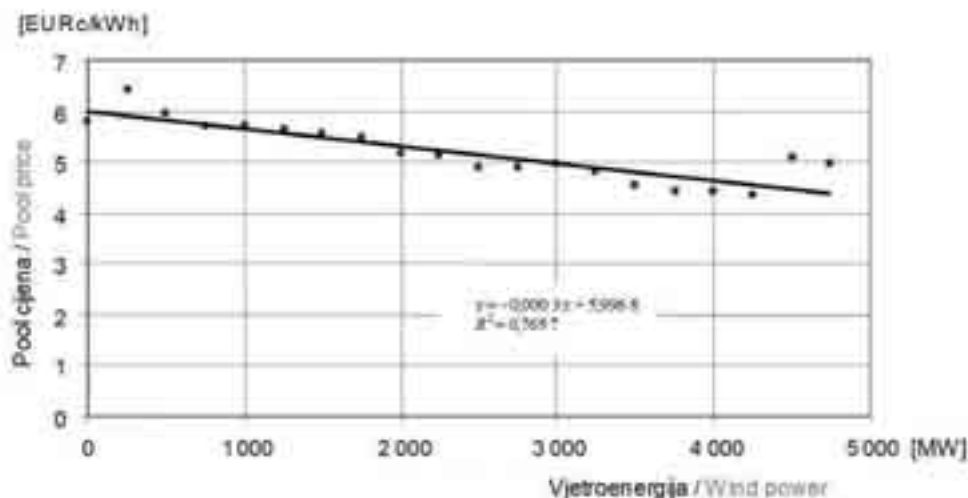
In late 2007, the total installed wind parks in Spain generated 15 145 MW.

Previously, the electricity produced by WPPs required changes in consumption management and had a slight effect on system operation. With time, the situation changed significantly, particularly with large-scale wind power integration into the system. An increasing number of WPPs are also connected to the 380/220 kV transmission system. Voltage, energy flows and power are becoming increasingly important and must be under constant supervision by the system operator (Figure 15).

Failure of a large number of WPPs caused by disturbances and faults in the transmission network affect the stability of the grid. WPPs are ordinarily located far from the consumption centers, a factor which has greatly affected the extension of electricity grids.

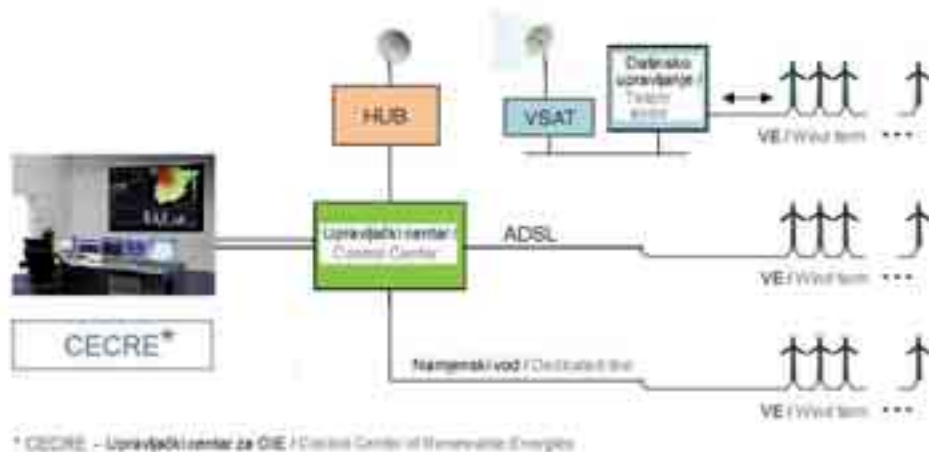
The requirements for the engagement of additional energy reserves due to the variable production of WPPs are less than anticipated. The results of the applied forecasting models have been increasingly favorable and the generation by WPPs in the general geographical area is reducing deviation from the plan.

Act 54/97 established the unbundling of the operations of electrical power companies, while retaining ownership over the means of production. Electrical power companies play an important role in the Span-



Slika 16 – Odnos između snage VE u sustavu i pool cijene na spot tržištu [19]

Figure 16 – The relationship between wind power in the system and pool prices on the spot market [19]



Slika 17 – Komunikacijske veze između VE i operatora sustava [19]
 Figure 17 – Communication between wind farms and the system operator [19]

Gotovo svi proizvođači električne energije i većina operatora VE nude svoju proizvodnju na tržištu električne energije. Operatori VE plaćaju operatoru sustava naknadu za usluge.

Uključivanjem sve većeg opsega VE smanjuje se cijena električne energije na spot tržištu (slika 16). Veće je smanjenje cijene električne energije na tržištu od rasta troškova uravnoteženja. Troškovi uravnoteženja sustava iznose oko 3,5 EURc/kWh.

VE imaju vrlo važnu ulogu u proširenju i pojačanju mreže. Fundamentalna je suradnja između sektora VE i operatora sustava. Ona je temelj uzajamnog razumijevanja i pronalaženja optimalnih tehničkih rješenja.

Obrađena je zajednička studija sektora vjetroenergije i operatora sustava koju je koordinirao glavni španjolski operator sustava REE. Istraženi su razni scenariji uključivanja VE prema predviđanju razine potrošnje električne energije tvrtke Iberian Electrical System i uz zahtjev da obilježja novih vjetroagregata budu u potpunosti usklađena sa zahtjevima mrežnih pravila [19].

Operator sustava utječe na sigurnost mreže koordinacijom pogona VE (slika 17).

U specifičnim čvorovima mreže pojavljuju se preopterećenja. Postoje rizici ispada pojedinih dijelova mreže zbog specifičnih problema dinamičke stabilnosti. U razdoblju niskih opterećenja pojavljuje se višak električne energije u sustavu.

Na EU razini treba provjeriti statičku i dinamičku sposobnost interkonekcijskih vodova između zemalja članica.

ish wind energy sector. Electrical power companies are the power plant operators and owners of 60 % of the Spanish production facilities.

Nearly all the producers of electricity and the majority of WPP operators offer their production on the electricity market. WPP operators pay the system operator a service fee.

With the increased integration of WPPs, the price of electricity on the spot market has fallen (Figure 16). There has been a greater price reduction for electricity on the market than the increase in balancing costs. Balancing costs of the system amount to approximately 3,5 EURc/kWh.

WPPs have a very important role in the extending and strengthening of grids. Cooperation between the wind power sector and system operator is fundamental. This is the basis of mutual understanding and the search for optimal technical solutions.

A joint study of the wind energy sector and system operator was coordinated by the main Spanish system operator, REE. Various scenarios have been investigated for the integration of WPPs according to the level of electricity consumption forecast by the firm Iberian Electrical System, with the requirement that the characteristics of new wind power plants should be completely coordinated with the requirements of the grid codes [19].

The system operator affects grid security through the coordination of WPP operation (Figure 17).

Overloads occur in specific network nodes. There are risks of the failure of individual parts of the grid due to specific problems of dynamic stability. During a period of low load, a surplus of electrical

Važno je pojačanje interkonekcijskih veza među zemljama članicama i uvođenje europskog dispečinga za upravljanje tokovima energije na europskoj razini i između zemalja članica.

Također, nužno je poboljšanje globalne prognoze vremena (vjetra).

U određenoj mjeri potrebno je i ujednačiti mrežna pravila na europskoj razini. Vjetroagregati moraju zadovoljavati mrežna pravila da bi se ostvarilo njihovo priključivanje na mrežu.

8.2 Njemački primjer [21]

Njemačka savezna vlada je usvojila plan izgradnje VE na moru ukupne snage 20 000 MW do 25 000 MW do 2030. godine. Na njemačkim potencijalnim lokacijama za izgradnju VE na moru postoje ozbiljni izazovi koji se uglavnom svode na veliku udaljenost VE od potrošačkih centara i na dubinu mora na potencijalnim lokacijama za izgradnju VE.

Na planiranim morskim lokacijama će se instalirati vjetroagregati jedinične snage 5,0 MW s ciljem smanjenja specifičnih troškova građenja. Odlučeno je da se na odabranoj test lokaciji izgradi 12 vjetroagregata, jedinične snage 5,0 MW koje je trebalo pustiti u pogon do ljeta 2008. godine.

Tri su ključna poduzeća koja će sudjelovati u izgradnji i pogonu VE na moru na test lokaciji, EWE, E.ON i Vattenfall. Vjetroagregate će proizvesti proizvođači REpower i Multibrid. Očekuje se da će uspješno izgrađena VE na test lokaciji predstavljati veliki skok u daljnjem korištenju energije iz VE na moru.

Poduzeće E.ON Netz u Schleswig-Holsteinu je pokazalo što se može postići primjenom inovativnih tehnologija. Od rujna 2006. godine sustav je u stanju pratiti temperaturu vodiča 110 kV vodova. E.ON Netz je uvjeren da će to povećati kapacitet mreže za 50 %. Studija koju je ugovorilo njemačko savezno ministarstvo za okoliš, predočilo je rezultate o mogućnosti 100 postotnog povećanja prijenosnih kapaciteta. Monitoring mjerenja temperature mogu se ugraditi i na vodove više naponske razine.

Njemački savezni parlament je prihvatio Zakon o bržoj izradi plana razvoja infrastrukture po kojem se njemački operatori sustava obvezuju izgraditi i održavati priključak VE

power occurs in a system.

At the level of the EU, it is necessary to verify the static and dynamic capabilities of the interconnection lines among Member States.

It is important to strengthen the interconnection lines among the Member States and introduce European dispatching for the management of energy flows at the European level among Member States.

Furthermore, it is necessary to improve global weather forecasting (wind).

To a specific extent, it is necessary to make grid codes uniform at the European level. Wind power plants must meet grid codes in order to be connected to the grid.

8.2 The German example [21]

The Federal Government of Germany has adopted a plan for the construction of offshore WPPs with a total capacity of 20 000 MW to 25 000 MW by the year 2030. At the potential German locations for the construction of offshore WPPs, there are serious challenges that in general refer to the great distance between the WPPs and consumer centers, as well as the sea depth at potential locations.

At the planned offshore locations, wind turbines with unit capacities of 5,0 MW will be installed, with the goal of reducing specific construction costs. Twelve wind turbines with unit capacities of 5,0 MW were scheduled to be built at a selected test location and in operation by the summer of 2008.

The three key enterprises that will participate in the construction and operation of the offshore WPPs at the test location are EWE, E.ON and Vattenfall. The wind turbines will be manufactured by REpower and Multibrid. It is anticipated that the successful construction of wind turbines at the test location will represent a great leap in the further use of energy from offshore WPPs.

The enterprise E.ON Netz in Schleswig-Holstein has demonstrated what can be achieved through the application of innovative technologies. Since September 2006, a system has been in place to monitor the conductor temperature on a 110 kV power line. E.ON Netz is convinced that this will increase grid capacity by 50 %. A study commissioned by the German Federal Ministry for the Environment predicted the possibility of a 100 % increase in transmission capacities. Conductor temperature measurement can also be installed for power lines of higher voltage levels.

The German Federal Parliament has adopted the Infrastructure Planning Acceleration Act, pursuant to which the German system operators will be required

na moru na svoj vlastiti trošak, kao što je to slučaj u Danskoj.

Taj novi zakonski akt otvara potpuno novo poglavlje na području opskrbe energijom u Njemačkoj. Zakonom se žele znatno smanjiti troškovi i otkloniti glavne prepreke u izgradnji VE na moru. Međutim, to nisu jedine koristi koje donosi novi zakon. On će omogućiti bolje povezivanje prijenosnih vodova mnogih VE, što je pozitivno i s aspekta zaštite okoline.

Taj zakon je korak prema ideji koju slijedi irska tvrtka Airtricity, a koja planira izgraditi europsku super mrežu VE na Sjevernom moru, kojom će se povezati VE snage 10 000 MW s njemačkom, nizozemskom i britanskom mrežom, do 2015. godine.

U Njemačkoj je uočeno da je nužna intenzivnija suradnja operatora sustava i sektora vjetroenergije. Treba istaknuti vrlo pozitivan primjer suradnje njemačke regulatorne agencije na obradi studije mogućnosti prihvata VE u njemački sustav (dena studija) [5]. Na tom primjeru se pokazalo da samo studije koje zajedno obrađuju operatori sustava, energetske regulatori, vjetroindustrija i operatori VE mogu ubrzati proces odlučivanja na stvarnim osnovama. Obrada paralelnih studija neće dati istovjetne rezultate.

Njemački operatori sustava surađuju s njemačkom industrijom VE na obradi druge faze dena studije. Studija ima za cilj da se utvrdi mogućnost i način uključivanja 25 % do 30 % obnovljivih izvora energije, uglavnom proizvodnje VE u elektroenergetski sustav do 2020. ili 2025. godine.

8.3 Francuski primjer [22]

Krajem 2007. godine u Francuskoj je bilo izgrađeno VE ukupne snage 2 454 MW. U srpnju 2005. godine usvojen je Zakon o energiji u kojem su pored ostalih odredbi, utvrđena geografska područja na kojim će se graditi nove VE.

Studije mogućnosti uključivanja VE u francuski elektroenergetski sustav su pokazale da prijenosna mreža može prihvatiti VE ukupne snage od 6 000 MW do 7 000 MW bez značajnijih pojačavanja mreže.

U prethodnom razdoblju je uočen nesklad između predviđanja razvoja korištenja energije vjetra i plana razvoja mreže te je nužna koordinirana suradnja na izgradnji VE i planiranju zahvata u prijenosnoj mreži.

to build and maintain connections to offshore WPPs at their own expense, as is the case in Denmark. This new legislation opens a completely new chapter in the area of energy supply in Germany. Through legislation, it is desired to reduce costs significantly and eliminate the main obstacles to the construction of offshore WPPs. However, these are not the only benefits that the new law brings. It will facilitate improved bundling of the transmission lines of many WPPs, which is also positive from the aspect of environmental protection.

This law is a step toward an idea that is being followed by the Irish company Airtricity, which plans to construct a European supergrid of WPPs on the North Sea and thereby connect WPPs of up to 10 000 MW to the German, Dutch and British grids by the year 2015.

In Germany, it has been noted that greater cooperation among system operators and the wind power sector is needed. It is necessary to point out the very positive example of cooperation by the German regulatory agency on a study to determine the possibility of integrating WPPs into the German system (the dena-grid study) [5]. In this example, it was shown that only studies with the joint participation of system operators, energy regulators, the wind power industry and WPP operators can accelerate the decision-making process on sound foundations. Conducting parallel studies would not produce the same results.

German system operators are cooperating with the German WPP industry on the second phase of the dena-grid study. The study has the goal of determining the feasibility and manner of integrating a 25 % to 30 % share of renewable energy sources, mainly WPP production, into the system by the year 2020 or 2025.

8.3 The French example [22]

At the end of the year 2007, WPPs were built in France with a total capacity of 2 454 MW. In July 2005, the Energy Act was adopted, in which, among other things, the geographic region in which new WPPs would be built was stipulated.

Feasibility studies on the integration of WPPs in the French electrical power system have shown that the transmission grid could accommodate WPPs with grid capacities of 6 000 MW to 7 000 MW without significant reinforcement.

During the previous period, a lack of coordination was noted between the anticipated development of the use of wind energy and the development plan of the grid. It is necessary to coordinate cooperation on the construction of WPPs and the planning of under-

Uočena je visoka promjenljivost proizvodnje električne energije na lokalnoj razini i bitno smanjena promjenljivost na nacionalnoj razini.

Snaga VE s kojom operator sustava može računati u sustavu za razinu uključenosti VE u sustav od nekoliko GW je oko 30 % od instaliranog kapaciteta VE, a za instalirani kapacitet VE od 20 GW je oko 15 % [5].

8.4 Talijanski primjer [23]

U Italiji je do kraja 2007. godine izgrađeno VE ukupne snage 2 726 MW. Na prijedlog TERNE usvojen je plan razvoja električne mreže, kojim se predviđa pokrivanje rastuće potrošnje električne energije, priključivanje novih proizvodnih objekata, uklanjanje zagušenja u mreži, povećanje učinkovitosti mreže te izgradnja novih interkonekcijskih vodova prema susjednim državama, uz ispunjavanje svih ekoloških zahtjeva.

U razdoblju od 2006. do 2010. godine predviđaju se investicijska ulaganja u prijenosnu mrežu od 1,6 milijardi eura, a nakon 2010. godine daljnjih 1,5 milijardi eura.

Predviđa se porast potrošnje električne energije od 330,4 TWh ostvarene 2005. godine na 369,3 TWh u 2010. godini i 420 TWh u 2020. godini. Predviđa se da će instalirana snaga VE iznositi 3 875 MW, 2008. godine.

S ciljem uključivanja većeg opsega VE u sustav, postavljaju se posebni zahtjevi na nove VE koje će se uključivati u sustav:

- sposobnost pogona tijekom poremećaja u mreži,
- udio VE u rješavanju tehničkih ograničenja u kritičnim situacijama u mreži,
- udio u regulaciji napona,
- udio u regulaciji frekvencije,
- prognoziranje proizvodnje VE.

8.5 Velika Britanija [24]

Ciljevi i težnje Velike Britanije su sljedeći:

- da obnovljivi izvori energije pokrivaju:
 - 10 % bruto potrošnje električne energije u 2010. godini,
 - 20 % bruto potrošnje električne energije u 2020. godini,
- VE će dati najveći doprinos ostvarenju toga cilja,
- nema posebnih ciljeva vezanih uz strukture VE na kopnu i VE na moru,

takings on the transmission grid.

The high variability in the generation of electricity at the local level and the significantly reduced variability at the national level were noted.

The capacity credit at the level of the integration of WPPs into a system of a few GW is approximately 30 % of the installed capacity of the WPPs, and for WPPs with an installed capacity of 20 GW it is approximately 15 % [5].

8.4 The Italian example [23]

By late 2007, WPPs had been constructed in Italy with a total capacity of 2 726 MW. At the proposal of TERNA, a plan was adopted for the development of the electricity grid, according to which coverage for increasing electricity consumption, connection of new generating facilities, elimination of grid congestion, increased grid efficiency, the construction of new interconnected power lines toward neighboring countries and meeting all the ecological requirements are anticipated. During the period from 2006 to 2010, an investment of 1,6 billion euros in the transmission grid is anticipated, as well as an additional 1,5 billion euros after the year 2010.

Growth is expected in the consumption of electrical power from 330,4 TWh in the year 2005 to 369,3 TWh in the year 2010 and 420 TWh in the year 2020. The installed capacity of WPPs is expected to be 3 875 MW in the year 2008.

With the goal of the large-scale integration of WPPs into the system, specific requirements have been established for new WPPs that will be included in the system:

- operational capability during grid disturbances,
- participation by WPPs in resolving technical restrictions, especially in critical grid situations,
- participation in voltage regulation,
- participation in frequency regulation,
- forecasting WPP production.

8.5 Great Britain [24]

The goals and aspirations of Great Britain are as follows:

- for renewable energy sources to cover:
 - 10 % of total electricity consumption in the year 2010,
 - 20 % of total electricity consumption in the year 2020,
- WPPs will make the greatest contribution to achieving this goal,
- There are no specific goals connected with the

- smanjenje CO₂ emisije za 60 % do 2050. godine.

Krajem 2007. godine je u Velikoj Britaniji bilo u pogonu 2 389 MW VE.

8.6 Hrvatska

Prema provedenim stručnim analizama u studiji Mogućnost prihvata i tehnički zahtjevi za vjetroelektrane, koju je za operatora sustava HEP OPS obradio Energetski institut Hrvoje požar (EIHP), u Republici Hrvatskoj je moguće izgraditi VE ukupne snage oko 3 400 MW. Zahvaljujući poticajima koji su predviđeni za proizvodnju električne energije iz obnovljivih izvora energije, domaći i strani investitori su razvili i pripremili projekte za izgradnju VE ukupne snage 1 578 MW.

Studijom je utvrđeno da su apsorpcijske mogućnosti postojeće mreže 923 MW. Regulacijske sposobnosti elektroenergetskog sustava dodatno ograničavaju mogućnost priključka VE na prijenosnu mrežu na ukupnu snagu VE od 300 MW do 400 MW.

Studijom se predlažu i mjere za povećanje prihvata VE u sustav:

- uvođenje prognoze proizvodnje VE 48 sati unaprijed,
- uvođenje naknada za pružanje usluga sustavu,
- nabava prekograničnih usluga sustavu,
- uključivanje većeg broja elektrana u sekundarnu *P/f* regulaciju,
- modernizacija upravljanja sustavom,
- pojačavanje, proširenje i izgradnja prijenosne mreže.

9 ISTRAŽIVANJA O MOGUĆNOSTIMA PRIHVATA VE U SUSTAV [25]

9.1 Studija o prihvatu VE u europski elektroenergetski sustav – (EWIS) studija

Do sada su obrađivane studije mogućnosti uključivanja VE u sustave pojedinih zemalja samo s nacionalnog stajališta. Nije bila obrađena zajednička studija na europskoj razini.

Potporna obnovljivim izvorima energije je ključno pitanje europske energetske politike. Da bi se svladali svi izazovi koji se pojavljuju na

- structure of onshore and offshore WPPs,
- There should be a 60 % reduction in CO₂ emissions by the year 2050.

At the end of the year 2007, wind power generation was 2 389 MW.

8.6 Croatia

According to professional analyses conducted within a study on the feasibility of the integration and technical requirements of wind power plants, performed for the system operator HEP OPS by the Energy Institute Hrvoje Požar (EIHP), in the Republic of Croatia it is possible to construct WPPs with a total capacity of approximately 3 400 MW. Owing to incentives that are anticipated for the production of electrical energy from renewable energy sources, domestic and foreign investors have developed and prepared projects for the construction of WPPs with a total capacity of 1 578 MW.

The study determined that the absorptive capacity of the existing grid is 923 MW. The secondary *P/f* control capabilities of the electrical power system additionally limit the possibility of the integration WPPs into the transmission grid to a total wind power capacity of 300 MW to 400 MW.

The study also proposes measures for increasing the integration of WPPs into the system:

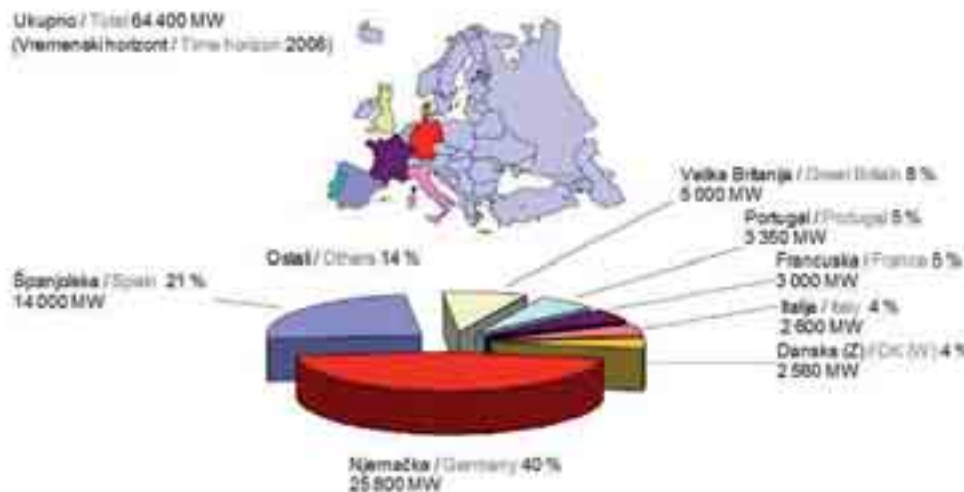
- the introduction of wind power generation forecasts 48 hours in advance,
- the introduction of compensation for providing system services,
- the procurement of trans-border system services,
- the integration of a large number of power plants into secondary *P/f* control,
- the modernization of the control system, and
- the strengthening, extension and construction of the transmission grid.

9 INVESTIGATION OF THE FEASIBILITY OF THE INTEGRATION OF WPPs INTO A EUROPEAN SYSTEM [25]

9.1 European Wind Integration Study – (EWIS)

Until now, discussion has focused upon feasibility studies on the integration of WPPs into the systems of individual countries, which were written solely from national perspectives, i.e. they were not joint studies at the European level.

Supporting renewable energy sources is a crucial



Slika 18 – Očekivana instalirana snaga u EU krajem 2008. [26]
Figure 18 – Predicted installed capacity in the EU at the end of 2008 [26]

putu ostvarenja te politike, na razini europskih operatora sustava (ETSO) pokrenuta je obrada studije prihvata VE u sustav s ciljem iznalaženja mjera, koje moraju poduzeti zakonodavci, regulatori, operatori i korisnici mreže, da bi se uspostavila usklađena pravila za prihvata VE u sustav. Ta su pravila bitna za sigurnost i pouzdanost pogona električnih mreža u kojim se pojavljuju sve veće količine promjenljive električne energije. Studijom su pokriveni svi tehnički, pogonski i tržišni aspekti uključivanja velikog opsega VE u europski sustav. Ključni cilj studije bio je dobiti potrebne informacije o tehničkim i pogonskim mjerama za ublažavanje rizika od mogućih ispada širih razmjera i siguran pogon europske mreže.

Pretpostavljeno je da će krajem 2008. godine snaga VE u EU porasti na 67 GW (slika 18). Najveći dio te snage koncentriran je u Njemačkoj, u kojoj VE čine 40 % ukupnog instaliranog proizvodnog kapaciteta. Njemačka, Španjolska i Velika Britanija raspolažu sa 70 % instaliranog kapaciteta u Europi. U studiji je pretpostavljen i rast proizvodnih kapaciteta u VE u Europi za 2015. godinu.

Povećavanje promjenljive proizvodnje električne energije u Europi bitno utječe na europski elektroenergetski sustav. Regionalno koncentrirana proizvodnja VE, poput one koja se ostvaruje u sjevernoj Njemačkoj rezultira povremenim velikim tokovima energije u susjednim elektroenergetskim sustavima. Ti neplanirani tokovi smanjuju stabilnost i nepovoljno utječu na raspoloživost kapaciteta za trgovinu električnom energijom.

Ublažavanje rizika ispada širih razmjera u Europi je vrlo upitno, zbog činjenice da u zemlja-

question in European energy policy. In order to overcome the challenges that have appeared on the path toward implementing this policy, at the level of the European Transmission System Operators (ETSO) a study has been launched on the integration of WPPs into the system with the goal of determining what measures should be undertaken by legislators, regulators, operators and grid users in order to establish harmonized regulations for the integration of WPPs. These regulations are essential for the security and reliability of the operation of electrical power grids in which there is increased variable power output. The study covers all the technical, operational and market aspects of the large-scale integration of WPPs into a European system. The key goal was to obtain the necessary information on the technical and operational measures to reduce the risk from potential major disturbances and assure the secure operation of the European grid.

It is assumed that in late 2008 the power of WPPs in the EU will increase to 67 GW (Figure 18). The majority of this power is concentrated in Germany, where WPPs make up 40 % of the total installed production capacity. Germany, Spain and Great Britain have 70 % of the total installed capacity in Europe. In the study, increased installed wind power capacity in Europe by the year 2015 was predicted.

Increased variable wind power generation in Europe significantly affects the European energy system. Concentrated regional wind power generation, such as that in northern Germany, has resulted in temporary large energy flows in neighboring electrical power systems. These unscheduled flows reduce stability and have an undesirable impact on the availability of capacities for electricity trading.

Mitigation of the risk of large-scale disturbances in

ma članicama EU postoje različita mrežna pravila, različiti načini regulacije tržišta i različiti poticaji za razvoj obnovljivih izvora energije. Ne postoji jedinstvena područja na kojima operatori, regulatori i tržišni subjekti mogu djelovati. Metode za ublažavanje rizika od ispada širih razmjera moraju se primijeniti istodobno u svim zemljama članicama. Koordinacija je iz tih razloga ključni zahtjev.

Daljnja istraživanja u okviru EWIS projekta odnose se na 2015. godinu. Ona će se odnositi na četiri područja:

- političke analize,
 - politička potpora i prioritete za pojačavanje i širenje električne mreže,
- pravne analize,
 - harmonizacija pravila,
 - poboljšanje zahtjeva mrežnih pravila za VE,
 - identifikacija pravnih prepreka,
- tržišne i poslovne analize,
 - prilagodba tržišnih pravila za uravnoteženje sustava,
 - integracija tržišta uravnoteženja,
 - harmonizacija regionalnih tržišta,
 - koordinacija operatora sustava na regionalnoj i unutar regionalne razine,
- tehničke analize,
 - pružanje informacija o vremenskim prognozama,
 - mogućnost upravljanja VE,
 - skladištenje većih količina električne energije,
 - automatizacija sustava za upravljanje u izvanrednim uvjetima.

9.2 Istraživanja u organizaciji Međunarodne agencije za energiju (IEA) u okviru projekta Wind Task 25 [27]

Međunarodna agencija za energiju (IEA) je 2006. godine pokrenula trogodišnji projekt pod nazivom Wind Task 25. Poznati su i prvi, zbirni rezultati nedavno obrađenih studija, preporuke i plan daljnjih aktivnosti na tom projektu. U obradu projekta i njegovo financiranje su uključene: EWEA udruga, Danska, Finska, Njemačka, Irska, Norveška, Nizozemska, Portugal, Španjolska, Švedska, Velika Britanija i SAD.

Sve se više VE priključuje na električnu mrežu. Troškovi priključenja postaju problem za mnoge zemlje. Teško je uspoređivati i procijeniti rezultate mnogih provedenih istraživanja, zbog primjene različitih metodologija i podataka kao i procedura u pogonu pojedinih sustava.

Europe is highly doubtful due to the fact that there are various grid codes, various types of market regulations and various forms of incentives for the development of renewable energy sources among the Member States of the EU. There are no uniform areas in which operators, regulators and market subjects can operate. The methods for risk mitigation from large-scale disturbances must be applied simultaneously in all the Member States. For these reasons, coordination is a crucial requirement.

Further investigation within the framework of the EWIS project will refer to the year 2015. It will cover four areas:

- political analyses,
 - political support and priorities for strengthening and extending electrical power grids,
- legal analyses,
 - harmonization of regulations,
 - improving the requirements of the grid codes for WPPs,
 - identification of the legal obstacles,
- market and business analyses,
 - coordination of market regulations for system balancing,
 - integration of market balancing,
 - harmonization of regional markets,
 - coordination of system operators at the regional and sub-regional levels,
- technical analyses,
 - providing information on weather forecasts,
 - control of WPPs,
 - storage of large quantities of electrical energy,
 - system automation for control under exceptional circumstances.

9.2 Investigation under the auspices of the International Energy Agency (IEA) within the framework of Wind Task 25 [27]

In the year 2006, the International Energy Agency (IEA) launched a three-year project entitled Wind Task 25. The initial results of the studies, recommendations and a plan for further activities in this project have been published. The EWEA, Denmark, Finland, Germany, Ireland, Norway, the Netherlands, Portugal, Spain, Sweden, Great Britain and the United States are included in the implementation and financing of the project.

An increasing number of WPPs are connected to the power grid. Connection costs have become a problem for many countries. It is difficult to compare and assess the results of many studies that have been conducted due to the application of various methodologies, data and procedures in the operations of individual systems.

9.3 Najnovija provedena istraživanja o mogućnostima prihvata VE u sustav u Europi i SAD-u

U najnovije vrijeme obrađene su studije mogućnosti prihvata VE nekoliko zemalja Europe i SAD (tablica 1).

10 ZAKLJUČAK

U članku su prezentirani podaci o institucionalnim okvirima i razvojnim perspektivama korištenja energije vjetra u proizvodnji električne energije u Europi. Predočeni su mnogi izazovi pred kojim stoje europske i nacionalne institucije u svladavanju prepreka bržem prihvatu električne energije VE u sustave zemalja članica EU.

Postojeća pričuvna snaga u sustavima pojedinih zemalja može se iskoristiti za uravnoteženje promjenljive proizvodnje VE, do relativno visoke razine uključenosti VE u sustavu.

U slučaju da VE pokrivaju 10 % do 15 % potrošnje električne energije u sustavu, potrebno je osigurati dodatnu pričuvnu snagu od 2 % do 4 % ukupne snage VE u sustavu. Troškovi dodatne pričuvne snage se procjenjuju na 1 EUR/MWh do 4 EUR/MWh proizvedene električne energije VE.

Da bi se ostvario ekonomičan dnevni pogon VE u sustavu potrebno je koristiti niz alata i mjera, kao što je primjena suvremenih metoda za kratkoročno prognoziranje proizvodnje VE, bolje korištenje postojećih interkonekcijskih vodova, poboljšanje pravila za energiju uravnoteženja, primjena upravljanja potrošnjom električne energije i skladištenje energije.

Organizacijom predviđanja proizvodnje VE na regionalnoj razini i korištenjem postojećih in-

9.3 The most recent investigations conducted on the feasibility of the integration of WPPs into the European and US systems

Most recently, studies have been conducted on the feasibility of the integration of WPPs by several European countries and the United States (Table 1).

10 CONCLUSION

Data have been presented on the institutional frameworks and development perspectives for the utilization of wind energy in the generation of electricity in Europe. Many challenges confronting the European and national institutions in overcoming the obstacles to the rapid integration of electricity from WPPs into the systems of the Member States of the EU have been discussed.

The existing power reserves in the systems of individual countries can be used for balancing the variable production of WPPs at up to relatively high levels of wind power integration.

In the event that WPPs cover 10 % to 15 % of the electricity consumption in a system, it is necessary to secure additional reserve power of 2 % to 4 % of the total power from WPPs in the system. The costs of the additional power reserves have been estimated as 1 EUR/MWh to 4 EUR/MWh for the electrical energy produced by WPPs.

In order to achieve the economical daily operation of WPPs in a system, it is necessary to use a series of tools and measures, such as applied modern methods for short-term forecasts of WPP generation, improved utilization of the existing interconnection lines,

Tablica 1 — Pregled najnovijih istraživanja mogućnosti prihvata VE u sustave pojedinih zemalja Europe i SAD-a

Table 1 — The most recent feasibility studies for the integration of WPPs into the systems of individual European countries and the United States

Država / Country	Vršno opterećenje u sustavu Peak load in system [GW]	Planirana snaga VE Planned wind power capacity [GW]	Postotak vršnog opterećenja Percentage of peak load [%]
Nordijske zemlje / Nordic countries	69	20	29
Velika Britanija / Great Britain	65	26	40
Irska / Ireland	6	2	33
Danska / Denmark			100
Nizozemska / The Netherlands	16	6	38
Njemačka / Germany	80	36	45
Portugal / Portugal	10	5	50
SAD / USA			
Minnesota	10	1,5	15
New York	33	3,3	10
Colorado	7	0,7 - 1,05	10 - 15
California			4

terkonekcijskih vodova u tom području, olakšava se uravnoteženje sustava i predviđanje proizvodnje VE.

Poboljšanjem infrastrukture mreže olakšava se uključivanje VE u sustav. Dodatni troškovi za pojačavanje mreže kreću se, prema rezultatima mnogih studija, između 0,1 EUR/MWh i 4,5 EUR/MWh električne energije proizvedene u VE.

Suvremene VE već danas ostvaruju visok stupanj tehnološke usklađenosti sa zahtjevima sustava.

Rezultati mnogih nacionalnih studija ukazuju na porast cijene električne energije kod krajnjih potrošača, koji je posljedica sve većeg opsega uključenosti VE u sustav. Povećanje cijene kod krajnjih potrošača se kreće između 2 EUR/MWh i 4 EUR/MWh proizvedene električne energije u VE za slučaj da pokrivaju do 15 % bruto potrošnje električne energije u sustavu.

improved regulations for energy balancing, control of electricity consumption and energy storage.

System balancing and wind power production forecasting are facilitated by the organization of wind power production forecasting at the regional level and the use of existing interconnection lines.

Integration of WPPs into a system is facilitated by improvement in the grid structure. Additional costs for strengthening the grid, according to the results of many studies, range between 0,1 EUR/MWh and 4,5 EUR/MWh for electricity generated by WPPs.

Contemporary WPPs are already achieving a high level of technological compliance with system requirements.

The results of many national studies point to increases in electricity prices for the final consumers due to the growing integration of WPPs into the systems. Higher prices for the final consumer range between 2 EUR/MWh and 4 EUR/MWh for energy generated by WPPs in the event that it covers up to 15 % of the total electricity consumption in a system.

LITERATURA / REFERENCES

- [1] Facts and Figures, VGB - Electricity Generation 2007
- [2] Large-scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations - Report by EWEA, December 2005
- [3] Green Paper on the Security of Energy Supply, EU Commission, 2000
- [4] Directive on Electricity Production from Renewable Energy Sources, 2001/77/EC, EU Commission, 2001
- [5] Energy Green Paper, EU Commission, 2006
- [6] Action Plan for Energy Efficiency, EU Commission, 2006
- [7] YORDY AQUIRRE, B., Renewable Energy Roadmap, Integrating Wind Power into the Grid - Link with European RES Directive, EWEC 2006
- [8] The European Wind Energy Platform (TPWind), 2007
- [9] European Wind Energy Integration Study (EWIS) - Towards a Successful Integration of Wind Power into European Electricity Grids, January 15, 2007
- [10] GARRARD, A., GARDNER, P., GARRARD HASSAN AND PARTNERS, Developments in Wind Turbine Technology and Energy Forecasting for High Wind Penetration, EWEC 2006
- [11] Strategic Energy Review - EU Commission, 2007
- [12] An Energy Policy for Europe - EU Commission, 2007
- [13] PIEBALGS, A., Large-scale Integration of Wind Energy in the European Power Supply - European Wind Energy Conference, (EWEC 2006) - Speaking points for the opening speech
- [14] HOPPE-KILPPER, M., Results from the Dena Grid Study, deENet, EWEC 2006
- [15] ZERVOS, A., Wind Power as a Mainstream Energy Source, EWEC 2006
- [16] Pure Power - Wind Energy Scenarios up to 2030, The European Wind Energy Association (EWEA), March 2008
- [17] NORMARK, B., Transmissions Technologies to Support Integration of Wind Power, EWEC 2006
- [18] HOLTTINEN, H., IEA Wind Task 25 - Estimating the Impacts of Wind Power on Power Systems
- [19] CEÑA, A., Past and Present of Wind Energy, The Spanish Experience, General Recommendations at EU Level - EWEC 2006
- [20] FERNÁNDEZ, J.L., Grid Codes for Wind Energy in Spain and Developments in Europe, EWEC 2006
- [21] Nick-LEPTIN, J., The Era of Offshore Wind Energy, EWEC 2006
- [22] BALEA, L., Wind Power Integration in the French Electricity System - Present Situation, Upcoming, Challenges
- [23] VALENTE, M., Wind Energy and Grid Development - The Italian Case, EWEC 2006
- [24] OVERTON, J., Development of Offshore Transmission in the UK, EWEC 2006
- [25] Delivering Energy and Climate Solutions (EWEA 2007 Annual Report)
- [26] MAAS, G., Preliminary Result/Scope of EWIS study
- [27] HOLTTINEN, H., Estimating the Impacts of Wind Power on Systems - First Results of IEA Collaboration - Wind Task 25

Adresa autora: Address of author:

Vladimir Dokmanović, dipl. ing.
Nalješkovićeva 23
10000 Zagreb
Hrvatska

Vladimir Dokmanović, Graduate Engineer
Nalješkovićeva 23
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2008-08-28

Manuscript received on:
2008-08-28

Prihvaćeno:
2008-09-22

Accepted on:
2008-09-22

PRIMJENA LINIJSKIH ODVODNIKA PRENAPONA ZA ZAŠTITU DALEKOVODA 110 kV STON - KOMOLAC OD ATMOSFERSKIH PRAŽNJENJA

APPLICATION OF LINE SURGE ARRESTERS IN THE PROTECTION OF THE 110 kV STON - KOMOLAC TRANSMISSION LINE FROM ATMOSPHERIC DISCHARGES

Miroslav Mesić – Milan Puharić – Dalibor Škarica, Zagreb, Hrvatska

Pouzdanost pogona prijenosne mreže u velikoj mjeri utječe na pouzdanost elektroenergetskog sustava i sigurnost opskrbe potrošača električnom energijom. Zbog specifičnog položaja u zoni intenzivnih atmosferskih pražnjenja DV 110 kV Ston – Komolac je u posljednjih 10 godina imao veliki broj ispada iz pogona čime su značajno smanjeni pouzdanost i sigurnost pogona tog dijela prijenosne mreže. Kao tehnički i ekonomski najpovoljnije rješenje za poboljšanje zaštite dalekovoda od atmosferskih pražnjenja odabrano je opremanje dalekovoda linijskim odvodnicima prenapona. Njihovom ugradnjom bitno su smanjeni broj i trajanje prekida pogona predmetnog dalekovoda radi prisilnih zastoja te povećana pouzdanost prijenosne mreže na širem dubrovačkom području.

Opremanje dalekovoda linijskim odvodnicima prenapona predstavlja temelj za pilot projekt monitoringa pogona dalekovoda za vrijeme atmosferskih pražnjenja. Iskustva i rezultati učinkovitosti primijenjene zaštite DV 110 kV Ston – Komolac od atmosferskih pražnjenja bit će podloga za daljnje primjene i na dalekovode viših naponskih razina.

The reliability of the operation of a transmission network largely influences the reliability of the power system and the security of the electricity supply to consumers. During the past 10 years, there have been a large number of outages of the 110 kV Ston – Komolac Transmission Line due to its specific location in a zone where the intensity of atmospheric discharge is high, which has thereby significantly reduced the reliability and security of the operation of that section of the transmission network. As the most technically and economically desirable solution for improving the protection of the transmission line from atmospheric discharges, it was decided to equip the transmission line with line surge arresters. Their installation significantly reduced the number and duration of forced outages and increased the reliability of the transmission network in the greater Dubrovnik region. Equipping the transmission line with line surge arresters was the basis for a pilot project of monitoring the operation of the transmission line during atmospheric discharges. The experiences and results regarding the efficiency of the protection of the 110 kV Ston – Komolac Transmission Line from atmospheric discharges will provide the basis for further applications on transmission lines of higher voltage levels.

Ključne riječi: atmosfersko pražnjenje; dalekovod; linijski odvodnik prenapona; pouzdanost; prijenosna mreža; prisilni zastoj

Key words: atmospheric discharge; forced outage; line surge arrester; reliability; transmission line; transmission network



1 UVOD

Prijenosna mreža zauzima središnje mjesto u elektroenergetskom sustavu i u tehnološkom lancu opskrbe potrošača električnom energijom.

Osnovni elementi prijenosne mreže su visokonaponski dalekovodi i transformatorske stanice i o pouzdanosti njihovog pogona bitno ovisi pouzdanost elektroenergetskog sustava i sigurnost opskrbe potrošača električnom energijom.

Pokazatelji pouzdanosti pogona dalekovoda broj su i trajanje prekida pogona do kojih može doći zbog različitih razloga.

Statistikom pogonskih događaja u prijenosnoj mreži [1] koja se vodi od 1995. godine zabilježen je neuobičajeno veliki broj prisilnih zastoja dalekovoda 110 kV Ston – Komolac, koji su za posljedicu imali smanjenu pouzdanost pogona tog dijela prijenosne mreže i sigurnosti napajanja šireg dubrovačkog područja električnom energijom.

Glavni razlog povećanog broja prisilnih zastoja DV 110 kV Ston – Komolac djelovanje je atmosferskih pražnjenja koja su na ovome području među najintenzivnijim u Hrvatskoj. Od nekoliko razmatranih mogućnosti za poboljšanje zaštite predmetnog dalekovoda od atmosferskih pražnjenja najprikladnijom je ocijenjena opcija ugradnje linijskih odvodnika prenapona, za koju su provedene potrebne analize i proračuni [2] i [3].

Nakon ugradnje linijskih odvodnika zabilježen je znatno manji broj i trajanje prekida pogona dalekovoda 110 kV Ston – Komolac čime je povećana pouzdanost prijenosne mreže i sigurnost opskrbe električnom energijom na tom području.

Opremanjem DV 110 kV Ston – Komolac linijskim odvodnicima prenapona i brojačima prorade odvodnika postignut je osnovni cilj – povećanje pouzdanosti pogona.

Za precizniju ocjenu primjene zaštite dalekovoda od atmosferskih pražnjenja u područjima visoke izokerauničke razine potrebni su podaci o stvarnim vrijednostima i obliku struje groma. Stoga se u nastavku pokrenuo pilot projekt opremanja dalekovoda DV 110 kV Ston – Komolac mjernim uređajima za snimanje oblika struja groma i daljinski prijenos podataka u informatički sustav korisnika u realnom vremenu.

Na temelju rezultata i primjene linijskih odvodnika prenapona za zaštitu DV 110 kV

1 INTRODUCTION

A transmission network occupies a central place in an electrical power system and the technological chain of supplying electricity to consumers.

The basic elements of a transmission network are high voltage transmission lines and substations. The reliability of their operation significantly influences the reliability of the electrical power system and the security of the electricity supply to consumers.

The indices of the reliability of the operation of a transmission line are the number and duration of outages, which can occur for various reasons.

Statistics on operational events in the transmission network [1] since 1995 have recorded an unusually large number of forced outages of the 110 kV Ston – Komolac Transmission Line, resulting in a reduction in the reliability of the operation of that part of the transmission line and the security of the electricity supply of the greater Dubrovnik region.

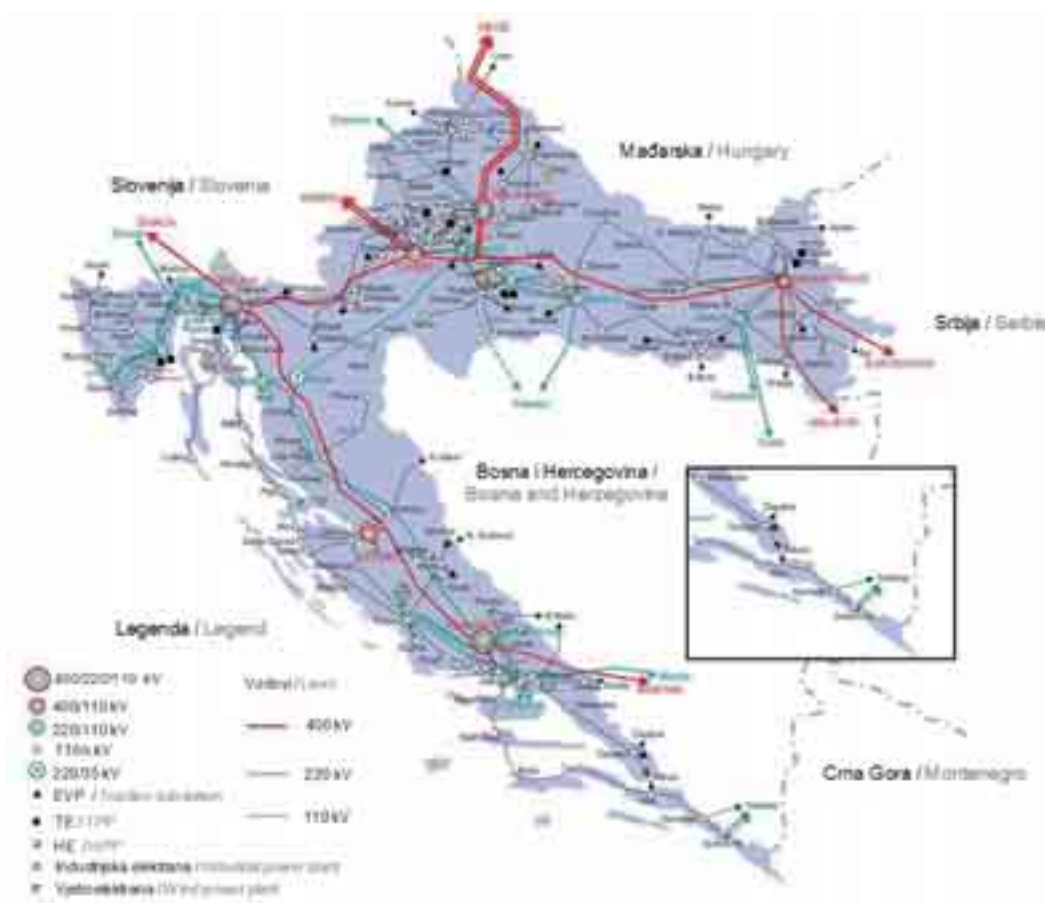
The main reason for the increased number of forced outages of the 110 kV Ston – Komolac Transmission Line is the activity of atmospheric discharges in this region, among the most intense in Croatia. Among the several options considered for improving the protection of this transmission line from atmospheric discharges, it was decided that the most suitable was the option of installing line surge arresters, for which the necessary analyses and calculations were performed, [2] and [3].

Following the installation of the line surge arresters, significantly fewer and shorter outages were recorded in the operation of the 110 kV Ston – Komolac Transmission Line, thereby increasing the reliability of the transmission network and the security of the electricity supply in this region.

By equipping the 110 kV Ston – Komolac Transmission Line with line surge arresters and surge counters, the main goal was achieved, i.e. increased reliability of operation.

In order to provide a precise assessment of the achieved degree of protection of the transmission line from atmospheric discharges in regions of high isokeraunic levels, the actual lightning current parameters are required. Therefore, another pilot project was inaugurated to equip the 110 kV Ston – Komolac Transmission Line with measuring devices for recording current waveforms and transmitting data to the remote computer system of the user in real time.

Based upon the results of the application of line surge arresters for the protection of the 110 kV Ston – Komolac Transmission Line from atmospheric discharges and the investigation conducted during the pilot project, a conclusion will be reached on the



Slika 1 – Shema hrvatskog elektroenergetskog sustava
Figure 1 – The Croatian electrical power system

Ston – Komolac od atmosferskih prenapona i istraživanja navedenog pilot projekta, donijet će se zaključak o primjeni linijskih odvodnika prenapona za zaštitu od atmosferskih pražnjenja i za dalekovode 220 kV i 400 kV prijenosne mreže u područjima intenzivne izokerauničke zone.

2 ANALIZA POUZDANOSTI POGONA DV 110 kV STON KOMOLAC

Dalekovod 110 kV Ston – Komolac ima važnu ulogu u prijenosnoj mreži, jer povezuje južni dio elektroenergetskog sustava i šire dubrovačko područje s ostalim dijelom sustava (slika 1).

Pouzdanost i sigurnost pogona DV 110 kV Ston – Komolac glavni su preduvjet sigurnog plasmana električne energije proizvedene u HE Dubrovnik u elektroenergetski sustav, te napajanja električnom energijom šireg

application of line surge arresters for the protection of the 220 kV and 400 kV transmission lines of the transmission network in regions of high isokeraunic activity from atmospheric discharges.

2 ANALYSIS OF THE RELIABILITY OF THE OPERATION OF THE 110 kV STON - KOMOLAC TRANSMISSION LINE

The 110 kV Ston – Komolac Transmission Line has an important role in the transmission network because it connects the southern part of the electrical power system and the greater Dubrovnik region with the other part of the system (Figure 1).

The reliability and security of the operation of the 110 kV Ston – Komolac Transmission Line are the chief prerequisites for the secure delivery of the electrical energy generated at the Dubrovnik Hydroelectric Power Plant to the electrical power system and the supply

dubrovačkog područja priključenog na TS 110/35 kV Komolac.

Kvarovi i ispadi predmetnog dalekovoda do vode do poremećaja pogona elektroenergetskog sustava i prekida opskrbe električnom energijom dubrovačkog područja, osobito osjetljivog na prekide opskrbe za vrijeme turističke sezone.

Osnovni tehnički podaci DV 110 kV Ston – Komolac (prije rekonstrukcije):

- godina izgradnje 1961.,
- duljina 43 959 m,
- broj stupova 144,
- vrsta stupova čelično-rešetkasti,
- vodiči Al/Če 150/25 mm²,
- zaštitno uže Če 50 mm²,
- izolatori porculan.

Tijekom 1994. godine radi povećanja prijenosne moći dalekovoda nužnog za plasman proizvodnje HE Dubrovnik u elektroenergetski sustav i povećanja pouzdanosti i sigurnosti pogona izvršena je njegova rekonstrukcija.

Rekonstrukcija dalekovoda obuhvatila je zamjenu vodiča, zaštitnog užeta i izolatora:

- godina rekonstrukcije 1994.,
- vodiči BTAL/Stalum 154/15 mm²,
- zaštitno uže Stalum 50 mm²,
- izolatori staklo.

Tablica 1 – Broj i trajanje prekida pogona DV 110 kV Ston – Komolac u razdoblju 1995. do 2006.

Table 1 – The number and duration of the outages of the 110 kV Ston – Komolac Transmission Line during the period from 1995 to 2006

Godina / Year	Godišnji broj prekida pogona / Annual number of outages	Trajanje prekida pogona / Duration of outages [h/god.] / [h/year]
1995.	23	8,23
1996.	25	5,58
1997.	24	7,95
1998.	21	6,16
1999.	30	9,56
2000.	14	4,76
2001.	13	57,48
2002.	24	2,53
2003.	12	3,46
2004.	14	18,38
2005.	18	5,26
2006.	17	1,45
Srednja vrijednost / Mean value	19,5	10,81

of electricity to the greater Dubrovnik region, which is connected to the 110/35 kV Komolac Substation.

Failures and outages of this transmission line lead to disturbances in the operation of the electrical power system and interruption in the supply of electricity to the Dubrovnik region, which is particularly sensitive to interruptions in supply during the tourism season.

The basic technical characteristics of the 110 kV Ston – Komolac Transmission System (prior to reconstruction) were as follows:

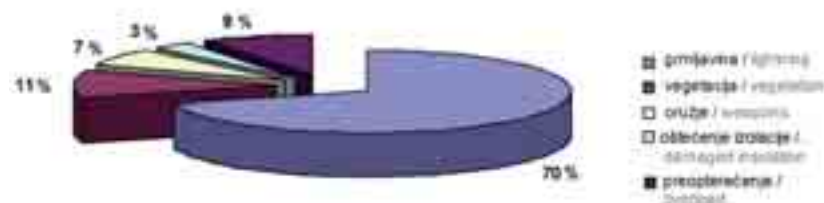
- year of construction: 1961,
- length 43 959 m,
- number towers 144,
- type of towers steel,
- conductors aluminum/steel 150/25 mm²,
- ground wire steel, 50 mm²,
- insulators porcelain.

During the year 1994, in order to increase the transmission capacity of the transmission line necessary for the delivery of the electrical energy generated by the Dubrovnik Hydroelectric Power Plant to the electrical power system and increasing the reliability and security of operation, it was reconstructed.

The reconstruction of the transmission line included the replacement of conductors, ground wire and insulation:

- year of reconstruction 1994,
- conductors BTAL/ACS 154/15 mm² (extra thermal resistant aluminum alloy/aluminium clad steel),
- ground wire ACS 50 mm²,
- insulators glass.

For the necessary communication between the information system of the Croatian Electrical Power Supply Company (HEP) and the process informatics



Slika 2 – Najčešći uzroci ispada dalekovoda iz pogona
Figure 2 – Most frequent causes of transmission line outages

Radi potrebe komunikacijskog povezivanja informatičkog sustava Hrvatske elektroprivrede i procesne informatike elektroenergetskog sustava klasično zaštitno uže zamijenjeno je 2007. godine novim zaštitnim užetom s optičkim nitima (OPGW).

Za analizu pouzdanosti pogona DV 110 kV Ston – Komolac uz navedene tehničke podatke bitni su i podaci o trasi dalekovoda:

- trasa je u blizini mora i nalazi se u specifičnim klimatskim uvjetima,
- trasa prolazi većinom brdovitim terenom,
- trasa je smještena u području jake i intenzivne izokerauničke zone.

U tablici 1 prikazani su podaci o broju i trajanju prekida pogona DV 110 kV Ston – Komolac u razdoblju 1995. do 2006. godine.

Podaci o broju i trajanju prekida pogona DV 110 kV Ston – Komolac prikazani u tablici 1 pokazuju izrazito veliki broj prekida pogona i dugo trajanje prekida pogona u razdoblju od 1995. do 2006. godine, što najbolje ilustriraju i srednje vrijednosti za razmatrano razdoblje.

Prema [2] na ispađe dalekovoda iz pogona utječe nekoliko razloga od kojih najveći udjel ima djelovanje atmosferskih pražnjenja (slika 2).

S obzirom na smještaj trase dalekovoda u području jakog i intenzivnog djelovanja atmosferskih pražnjenja i najvećeg broja grmljavinskih dana u godini u Hrvatskoj (70 dana), broj prekida pogona razmatranog dalekovoda bitno je veći u odnosu na broj prekida pogona u hrvatskoj prijenosnoj mreži.

U tablici 2 prikazana je usporedba vrijednosti učestalosti prisilnih zastoja i srednjeg trajanja prekida radi prisilnih zastoja dalekovoda u prijenosnoj mreži Hrvatske i dalekovoda 110 kV Ston – Komolac za razdoblje 2002. do 2006. godine.

Vrijednosti učestalosti prisilnih zastoja i srednjeg trajanja prisilnih zastoja dalekovoda izračunati su prema izrazima:

of the electrical power system, standard ground wire was replaced in the year 2007 with new composite ground wire with optical fiber (OPGW).

For the analysis of the reliability of the operation of the 110 kV Ston – Komolac Transmission Line, in addition to the aforementioned technical data, data on the transmission line route are essential:

- the route is near the sea and subject to specific climatic conditions,
- the route passes primarily through mountainous terrain,
- the route is located in a region characterized by a high isokeraunic level.

Table 1 presents data on the number and duration of the outages of the 110 kV Ston – Komolac Transmission Line during the period from 1995 to 2006.

Data on the number and duration of the outages of the 110 kV Ston – Komolac Transmission Line presented in Table 1 show the large number and long duration of the outages during the period from 1995 to 2006, as best illustrated by the mean values for the period studied.

According to Ref. [2], several factors influence transmission line outages, of which atmospheric discharges have the greatest share (Figure 2).

Since the transmission line is located in a region of strong and intense atmospheric discharge activity with the largest number of thunder days per year in Croatia (70 days), the number of outages of the transmission line studied is significantly greater in comparison to the number of outages in the Croatian transmission network as a whole.

Table 2 presents a comparison of the values of the rate of forced outages and the mean duration of outages due to forced outages in the transmission lines of the transmission network of Croatia and the 110 kV Ston – Komolac Transmission Line for the period from 2002 to 2006.

The values of the rate of the forced outages and the mean duration of the forced outages are calculated according to the following expressions:

$$f_{PZI} = \frac{N_{PZI}}{l_{DVM}} \left[\frac{1}{\text{km} \cdot \text{god.}} \right] \quad (1)$$

gdje su:

N_{PZI} – ukupni broj prisilnih zastoja dalekovoda 110 kV,
 l_{DVM} – ukupna duljina dalekovoda 110 kV,

where:

N_{PZI} – the total number of forced outages of the 110 kV line,
 l_{DVM} – the total length of the 110 kV transmission line,

$$f_{PZII} = \frac{N_{PZII}}{l_{DVSK}} \left[\frac{1}{\text{km} \cdot \text{god.}} \right], \quad (2)$$

gdje su:

N_{PZII} – ukupni broj prisilnih zastoja DV 110 kV Ston – Komolac,
 l_{DVSK} – duljina DV 110 kV Ston – Komolac,

where:

N_{PZII} – the total number of the forced outages of the 110 kV Ston – Komolac Transmission Line,
 l_{DVSK} – the length of the 110 kV Ston – Komolac

$$T_{SRI} = \frac{T_{UI}}{l_{DVM}} \quad [\text{h}] \quad (3)$$

gdje je:

T_{UI} – ukupno trajanje prisilnih zastoja svih dalekovoda 110 kV u Hrvatskoj.

where:

T_{UI} – the total duration of the forced outages of all the 110 kV transmission lines in Croatia.

Tablica 2 – Usporedba učestalosti i srednjeg trajanja prisilnih zastoja dalekovoda 110 kV prijenosne mreže Hrvatske i DV 110 kV Ston – Komolac
Table 2 – Comparison of the rate and mean duration of the forced transmission line outages of the 110 kV Croatian transmission network and the 110 kV Ston – Komolac Transmission Line

Godina / Year	$f_{PZ} [1 / \text{km} \cdot \text{god.}] / [1 / \text{km} \cdot \text{year}]$		$T_{SR} [\text{h}]$		Omjer / Ratio	
	f_{PZI}	f_{PZII}	T_{SRI}	T_{SRII}	f_{PZII} / f_{PZI}	T_{SRII} / T_{SRI}
2002.	0,069	0,54	3,7	0,105	7,82	0,028
2003.	0,085	0,27	10,1	0,288	3,17	0,028
2004.	0,076	0,32	8,3	1,310	4,21	0,157
2005.	0,065	0,41	4,4	0,292	6,30	0,066
2006.	0,072	0,39	2,6	0,085	5,41	0,032
Srednja vrijednost / Mean value	0,073	0,39	5,8	0,412	5,28	0,071

f_{PZI} – učestalost prisilnih zastoja dalekovoda 110 kV / rate of forced 110 kV Croatian transmission line outages

f_{PZII} – učestalost prisilnih zastoja DV 110 kV Ston – Komolac / rate of forced outages of the 110 kV Ston – Komolac Transmission Line

T_{SRI} – srednje trajanje prisilnih zastoja 110 kV dalekovoda u Hrvatskoj / mean duration of the forced 110 kV Croatian transmission line outages

T_{SRII} – srednja vrijednost prisilnih zastoja dalekovoda 110 kV Ston - Komolac / mean duration of the forced outages of the 110 kV Ston – Komolac Transmission Line

$$T_{SRII} = \frac{T_{UII}}{I_{DVSK}} \text{ [h]} \quad (4)$$

gdje je:

T_{UII} – ukupno trajanje prisilnih zastoja DV 110 kV Ston - Komolac.

Iz tablice 2 je vidljivo da je u razdoblju od 2002. do 2006. godine učestalost prisilnih zastoja DV 110 kV Ston - Komolac višestruko veća od prosječne učestalosti zastoja dalekovoda 110 kV prijenosne mreže.

Također je vidljivo da je srednja vrijednost trajanja prisilnih zastoja DV 110 kV Ston - Komolac višestruko manja od srednje vrijednosti trajanja prisilnih zastoja dalekovoda 110 kV prijenosne mreže.

Izražena učestalost i relativno kratko trajanje prisilnih zastoja su glavne značajke prisilnih zastoja dalekovoda koji nastaju radi atmosferskih pražnjenja.

Podaci o prisilnim zastojima u tablici 1 i u tablici 2, značajke prisilnih zastoja te činjenica da je trasa DV 110 kV Ston - Komolac smještena u jakoj i intenzivnoj izokerauničkoj zoni pokazuju da atmosferska pražnjenja negativno utječu na pouzdanost pogona predmetnog dalekovoda i pripadajućeg dijela elektroenergetskog sustava.

3 UGRADNJA LINIJSKIH ODVODNIKA PRENAPONA

Podaci o pouzdanosti pogona DV 110 kV Ston - Komolac u razdoblju od 1995. do 2006. godine te pretpostavka kako su najčešći uzrok prisilnih zastoja atmosferska pražnjenja, upućuju na zaključak da postojeća zaštita predmetnog dalekovoda od atmosferskih pražnjenja pomoću zaštitnog užeta nije dovoljna.

Zbog povećanja pouzdanosti pogona stoga je DV 110 kV Ston - Komolac bilo nužno dodatno zaštititi od atmosferskih pražnjenja. Dodatnu zaštitu DV 110 kV Ston - Komolac moguće je ostvariti primjenom nekoliko tehničkih mogućnosti:

- pojačanje izolacije,
- ugradnja dodatnog zaštitnog užeta,
- poboljšanje otpora uzemljenja,
- ugradnja linijskih odvodnika prenapona.

where:

T_{UII} – the total duration of the forced outages of the 110 kV Ston - Komolac Transmission Line.

From Table 2, it is evident that during the period from 2002 to 2006, the rate of the forced outages of the 110 kV Ston - Komolac Transmission Line was several times greater than the average transmission line outages of the 110 kV Croatian transmission network.

Furthermore, it is evident that the mean value of the duration of the forced outages of the 110 kV Ston - Komolac Transmission Line is several times lower than the mean value of the duration of the forced transmission line outages of the 110 kV Croatian transmission network.

The marked rate and relatively brief duration of the forced outages are the main characteristics of the forced transmission line outages that occur due to atmospheric discharges.

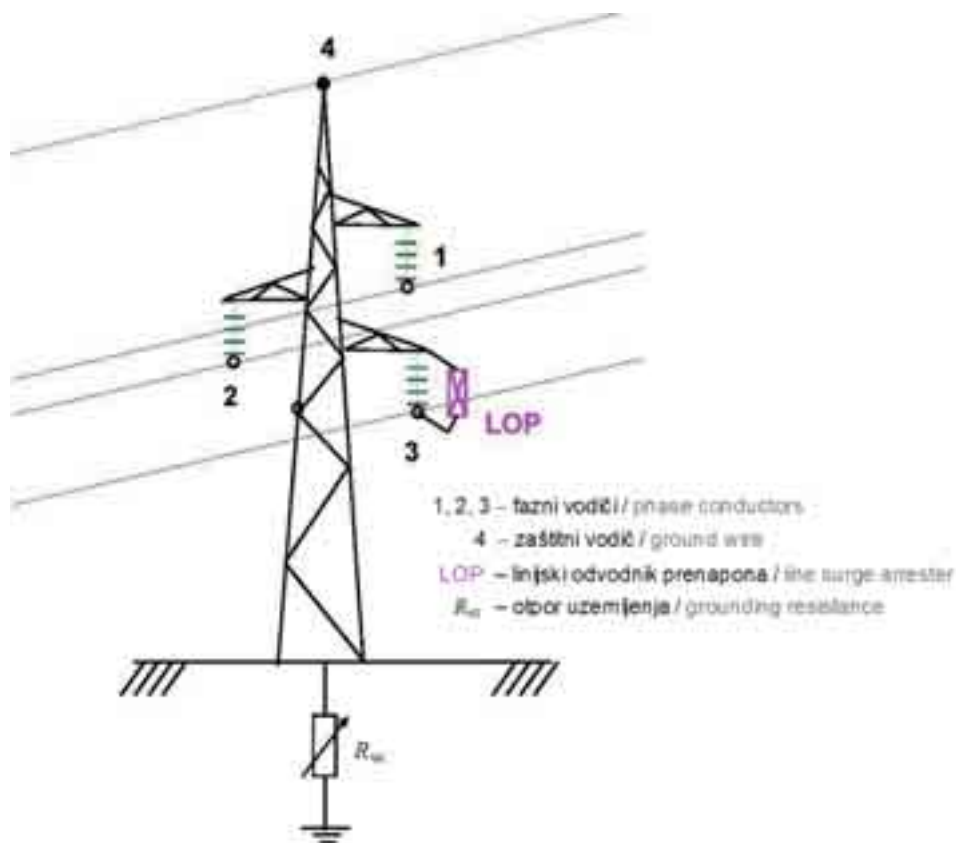
Data on forced outages in Tables 1 and 2, the characteristics of forced outages and the fact that the route of the 110 kV Ston - Komolac Transmission Line is located in a zone with a high isokeraunic level indicate that atmospheric discharges have a negative impact on the reliability of the operation of this transmission line and the corresponding part of the electrical power system.

3 INSTALLATION OF LINE SURGE ARRESTERS

Data on the reliability of the operation of the 110 kV Ston - Komolac Transmission Line during the period from 1995 to 2006 and the hypothesis that the most frequent cause of forced outage is atmospheric discharge led to the conclusion that the existing protection of the transmission line from atmospheric discharges using ground wire had been inadequate.

In order to increase the reliability of the 110 kV Ston - Komolac Transmission Line, it was necessary to provide additional protection from atmospheric discharges. There were several technical options for providing additional protection of the 110 kV Ston - Komolac Transmission Line:

- strengthening insulation,
- installing additional ground wire,
- reducing grounding resistance,
- installing line surge arresters.



Slika 3 – Mjesto ugradnje linijskog odvodnika prenapona na stupu dalekovoda
 Figure 3 – Line surge arrester installed on a transmission line tower

Tehnički i ekonomski i posebice u odnosu na zahtijevanu brzinu izvođenja zahvata uvjetovanu ograničenim vremenom isključenja dalekovoda iz pogona, najpovoljnija je opcija ugradnja linijskih odvodnika prenapona. Linijski odvodnik prenapona ugrađuje se između faznog vodiča i čelične konstrukcije stupa dalekovoda, poštujući pritom dopuštenu udaljenost vodiča pod naponom i spoja odvodnika na uzemljenu čeličnu konstrukciju stupa (slika 3).

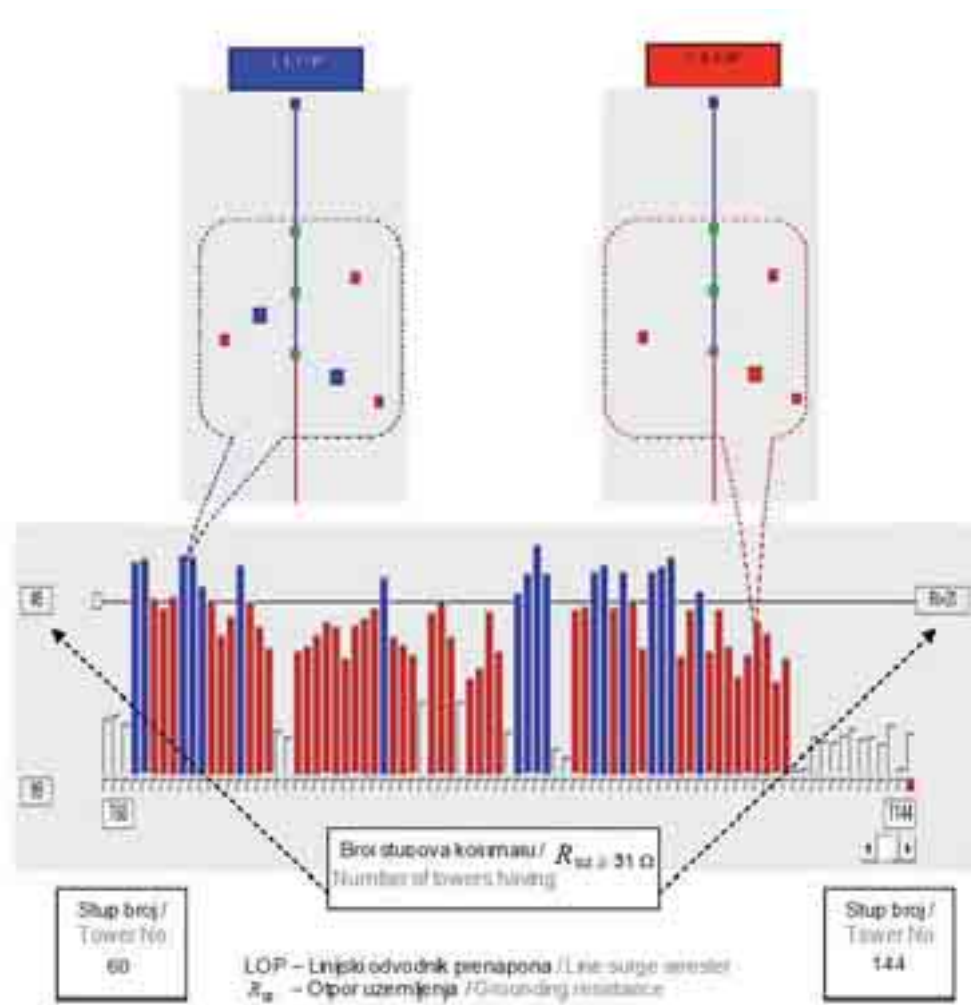
Odabir stupova dalekovoda na koje će se ugraditi odvodnici, odabir broja odvodnika po stupu (1 ili 2), te mjesta ugradnje po fazama prema [3] određen je posebnim računalnim programom [2] koji za različite otpore uzemljenja stupova određuje najpovoljniji broj i raspored odvodnika prenapona.

Za konačnu odluku o odabiru mjesta ugradnje i kombinacije odvodnika po fazama uz rezultate navedenog računalnog programa uzima se u obzir analiza prisilnih zastoja dalekovoda u prošlom razdoblju te raspoloživi meteorološki podaci.

From the technical and economic points of view, particularly regarding the time required for the implementation of the undertaking due to the limited acceptable downtime for the transmission line, the optimal choice was the installation of line surge arresters. Each line surge arrester was installed between the phase conductor and the steel tower structure of a transmission line, complying with the permitted distance between the live conductor and the connection point of the surge arrester to the grounded steel tower structure (Figure 3).

The selection of the transmission line towers on which the surge arresters were installed, the determination of the number of arresters per tower (1 or 2) and the site of installation according to phases as specified in Reference [3] were established by a special software program, [2], which determines the optimal number and distribution of surge arresters for various tower footing resistances.

For the final decision on the choice of the installation site and the combination of arresters according to phases, together with the results of the aforementioned software program, analysis of the forced outages of the transmission line during the previous period and the available meteorological data were taken into account.



Slika 4 – Primjer konfiguracije odvodnika prenapona za zaštitu DV 110 kV Ston - Komolac od atmosferskih pražnjenja (dionica od stupa 60 - 144)

Figure 4 – Example of a configuration of surge arresters for the protection of the 110 kV Ston - Komolac Transmission Line from atmospheric discharges (The section between Towers 60 - 144)

Na taj način utvrđena je i konfiguracija linijskih odvodnika prenapona za zaštitu DV 110 kV Ston - Komolac od atmosferskih pražnjenja (slika 4).

In this manner, the configuration of the line surge arresters for the protection of the 110 kV Ston – Komolac Transmission Line from atmospheric discharges was determined (Figure 4).

Ugradnja linijskih odvodnika prenapona i brojača za registraciju prorada odvodnika i struja odvoda na DV 110 kV Ston - Komolac obavljena je u ljeto 2007. godine u trajanju od 2 tjedna, a obuhvatila je:

The installation of line surge arresters and surge counters for the registration of the number of discharges through surge arresters and arrester discharge currents on the 110 kV Ston – Komolac Transmission Line was performed during a 2-week period in the summer of 2007, and included the following:

- | | | | |
|---------------------------------------------|------|----------------------------------------|------|
| – ukupni broj linijskih odvodnika prenapona | 110, | – total number of line surge arresters | 110, |
| – broj stupova s odvodnicima | 86, | – broj stupova s odvodnicima | 86, |
| – broj stupova s odvodnikom u | | – broj stupova s odvodnikom u | |
| | | in the low phase | 62, |

Tablica 3 - Usporedba prisilnih zastoja DV 110 kV Ston - Komolac prije i poslije ugradnje linijskih odvodnika prenapona

Table 3 - A comparison of the forced outages of the 110 kV Ston - Komolac Transmission Line before and after the installation of line surge arresters

Prisilni zastoji / Forced outages						
Prije ugradnje / Before installation			Poslije ugradnje / After installation			
2006-06-20 do / to 2007-03-31/			2007-07-20 do / to 2008-03-31 /			
Godina / Year	Mjesec/dan / Month/day	Trajanje / Duration [min]	Godina / Year	Mjesec/dan / Month/day	Trajanje / Duration [min]	
2006.	08-07	4	2007.	09-19	7	
	08-12	2				7
		3			10-31	38
	08-25	2			11-17	3
		4		2008.	03-24	26
	08-27	8				
	09-15	15				
	09-16	2				
	09-18	3				
		09-20	18			
	10-04	2				
2007.	01-23	4				

- donjoj fazi 62,
- broj stupova s odvodnicima u donjoj i srednjoj fazi 24,
- broj brojača prorade odvodnika 49,
- broj stupova s jednim brojačem 21,
- broj stupova s dva brojača 14.

- number of towers with arresters in the low and medium phases 24,
- number of arrester discharge counters 49,
- number of towers with one counter 21,
- number of towers with two counters 14.

Osnovni tehnički podaci polimernih metaloksidnih linijskih odvodnika prenapona:

The basic technical data on metal oxide line surge arresters with polymer housing are as follows:

- nazivni napon 108 kV,
- maksimalni pogonski napon 86 kV,
- nominalna struja pražnjenja 10 kA,
- IEC klasa II,
- masa 30 kg,
- visina 1147 mm,
- temperaturno područje -40 °C do +50 °C.

- nominal voltage 108 kV,
- maximum continuous operating voltage 86 kV,
- nominal discharge current 10 kA,
- IEC class II,
- mass 30 kg,
- height 1147 mm,
- temperature range -40° C to +50° C.

Podaci o proradi odvodnika prenapona i struji odvoda koje registrira brojač periodički se očitavaju sa zemlje pomoću posebnog instrumenta, te pohranjuju u bazu podataka.

Data on the surge arrester currents and the number of discharges registered by the counters are periodically read from the ground using a special instrument and stored in a database.

4 OCJENA UČINKA LINIJSKIH ODVODNIKA PRENAPONA NA POBOLJŠANJE POUZDANOSTI POGONA DV 110 kV STON - KOMOLAC

4 EVALUATION OF THE IMPACT OF LINE SURGE ARRESTERS ON IMPROVING THE RELIABILITY OF THE OPERATION OF THE 110 kV STON - KOMOLAC TRANSMISSION LINE

U prvoj godini pogona DV 110 kV Ston - Komolac s ugrađenim linijskim odvodnicima

During the first year of the operation of the 110

prenapona zabilježen je dvostruko maji broj prisilnih zastoja nego u istom razdoblju prethodne godine čime je ostvarena veća pouzdanost pogona i sigurnost opskrbe električnom energijom na širem dubrovačkom području.

Usporedba prisilnih zastoja prije i poslije ugradnje odvodnika opisana u [4] prikazana je u tablici 3.

Analiza podataka prikupljenih brojačem prorada pokazuje značajnu aktivnost odvodnika i dokazuje visoku izokerauničku razinu područja kojim prolazi trasa dalekovoda, a detaljni podaci o aktivnosti odvodnika po fazama i stupovima upućuju na najugroženija mjesta u pogledu utjecaja atmosferskih pražnjenja.

Bolja ocjena učinka linijskih odvodnika prenapona na poboljšanje pouzdanosti pogona DV 110 kV Ston - Komolac moći će se dati daljim praćenjem prisilnih zastoja i analizom podataka brojača prorade.

Usporedba konfiguracije linijskih odvodnika prenapona dobijena računalnim programom i podataka o prisilnim zastojima i proradi brojača predmetnog dalekovoda može potvrditi izabranu konfiguraciju odvodnika, ili uputiti na korekcije konfiguracije – premještaj postojećih, ili ugradnju dodatnih linijskih odvodnika prenapona.

5 PILOT PROJEKT MONITORINGA POGONA LINIJSKIH ODVODNIKA PRENAPONA DV 110 kV STON - KOMOLAC

Ugradnjom linijskih odvodnika prenapona na DV 110 kV Ston - Komolac ostvaren je temeljni postavljeni cilj – smanjivanje broja i trajanja prisilnih zastoja dalekovoda i povećanje pouzdanosti pogona.

Za cjelovitu ocjenu svih učinaka zaštite dalekovoda od atmosferskih pražnjenja i primjenu na postojećim i novim dalekovodima viših naponskih razina u sličnim izokerauničkim zonama, uz stalno praćenje i analizu pogona DV 110 kV Ston - Komolac, nužna su dodatna mjerenja i snimanja oscilograma struja groma koja bi pridonijela kvaliteti simulacije atmosferskih pražnjenja i određi-

kV Ston – Komolac Transmission Line after the line surge arresters were installed, a two-fold reduction in the number of forced outages in comparison to the same period of the previous year was recorded, thereby achieving increased reliability of operation and security of the supply of electricity to the greater Dubrovnik region.

A comparison of forced outages before and after the installation of the surge arresters, described in Ref. [4], is presented in Table 3.

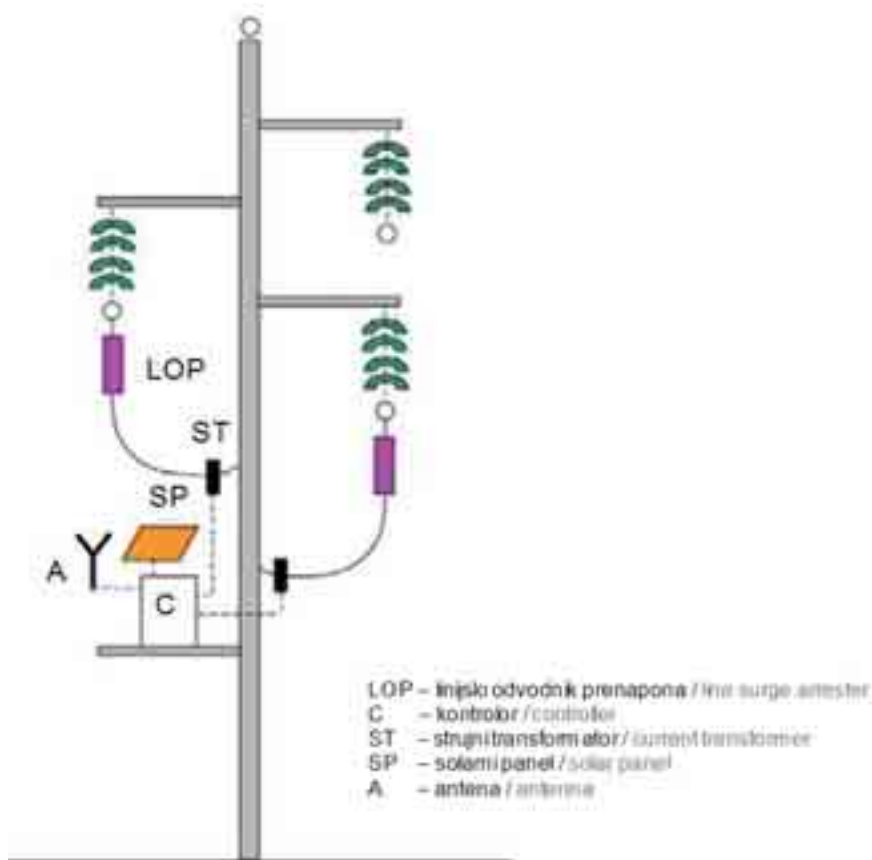
Analysis of the data collected with the surge counters indicates significant surge arrester activity and a high isokeraunic level of the region through which the transmission line passes. Detailed data on the surge arrester activity according to phases and towers indicate which places are the most vulnerable to atmospheric discharges. Further assessment of the impact of the line surge arresters on improving the reliability of the operation of the 110 kV Ston – Komolac Transmission Line will be possible after additional monitoring of the forced outages and analysis of the surge counter data.

Comparison of the configuration of the line surge arresters obtained using the software program and data on forced outages and surge counters could either confirm the selected surge arrester configuration or suggest a correction in the configuration, the relocation of existing line surge arresters or the installation of additional ones.

5 PILOT PROJECT ON MONITORING THE OPERATION OF THE LINE SURGE ARRESTERS OF THE 110 kV STON – KOMOLAC TRANSMISSION LINE

With the installation of line surge arresters on the 110 kV Ston – Komolac Transmission Line, the basic goal has been achieved, i.e. a reduction in the number and duration of the forced outages of the transmission line and an increase in the reliability of operation.

For an overall assessment of the effects of the protection of the transmission line from atmospheric discharges and the application on existing and new transmission lines of higher voltage levels in zones with similar isokeraunic levels, together with the constant monitoring and analysis of the operation of the 110 kV Ston – Komolac Transmission Line, additional measurements



Slika 5 – Monitoring pogona linijskih odvodnika prenapona
Figure 5 – Monitoring the operation of line surge arresters

vanja optimalnog broja i konfiguracije linijskih odvodnika prenapona za zaštitu dalekovoda od atmosferskih pražnjenja.

S tim ciljem pokrenut je pilot projekt monitoringa pogona linijskih odvodnika prenapona DV 110 kV Ston - Komolac koji predviđa ugradnju 2 uređaja za registraciju i oscilografiranje struje groma na mjestima gdje su zabilježena intenzivna atmosferska pražnjenja.

Oscilogrami struje groma prenosit će se do računala bežičnim komunikacijskim putem do transformatorske stanice i interne računalne mreže ili, ako bude izvedivo, direktno priključkom uređaja na optičke niti u zaštitnom užetu predmetnog dalekovodnog stupa (slika 5).

Pilot projekt predviđa prikupljanje, obradu i analizu podataka o prisilnim zastojjima, broju prorada brojača, struji odvoda odvodnika i oscilograma struja groma predmetnog dalekovoda u razdoblju od dvije godine.

are necessary. Oscillograms of the lightning current could contribute to the quality simulation of the atmospheric discharges and the determination of the optimal number and configuration of line surge arresters for the protection of the transmission lines from atmospheric discharges.

With this goal, a pilot project has been launched for the monitoring of the operation of the line surge arresters on the 110 kV Ston – Komolac Transmission Line, which anticipates the installation of two devices for registering and recording lightning currents at locations where intense atmospheric discharges have been noted.

Oscillograms of lightning current will be transmitted wirelessly to a computer, substation and the internal computer network or, if feasible, via direct connection of the device to the optical fiber ground wire of the transmission line tower (Figure 5).

The pilot project anticipates the collection, processing and analysis of transmission line data on forced

Rezultati navedenih analiza i istraživanja pokazat će učinkovitost primijenjene konfiguracije linijskih odvodnika prenapona za zaštitu dalekovoda od atmosferskih pražnjenja te ukazati na potrebu premještanja postojećih i eventualnog dodavanja novih odvodnika prenapona.

Poznavanje oscilograma i značajki stvarnih struja groma bit će temelj za poboljšanja kvalitete ulaznih podataka i simulacija računalnog programa za određivanje optimalne konfiguracije linijskih odvodnika prenapona, a time i poboljšanje učinkovitosti zaštite dalekovoda od atmosferskih pražnjenja.

Na temelju rezultata pilot projekta donijet će se također i zaključak o daljoj primjeni linijskih odvodnika prenapona za zaštitu dalekovoda 110 kV, 220 kV i 400 kV od atmosferskih pražnjenja u prijenosnoj mreži Hrvatske.

6 ZAKLJUČAK

DV 110 kV Ston - Komolac osobito je značajan u prijenosnoj mreži Hrvatske radi plasmata proizvodnje električne energije HE Dubrovnik u elektroenergetski sustav, te napajanja električnom energijom šireg dubrovačkog područja.

Trasa DV 110 kV Ston - Komolac prolazi područjem intenzivne izokerauničke zone s približno 70 grmljavinskih dana u godini, te učestalim i jakim atmosferskim pražnjenjima.

Zbog toga je u pogonu tog dalekovoda u razdoblju od 1995. do 2006. godine zabilježen veliki broj i trajanje prisilnih zastoja koji su znatno veći od prosjeka u prijenosnoj mreži Hrvatske.

S ciljem zaštita od atmosferskih pražnjenja, poboljšanja pouzdanosti pogona i povećanja sigurnosti opskrbe električnom energijom dubrovačkog područja na DV 110 kV Ston - Komolac u ljeto 2007. godine ugrađeni su linijski odvodnici prenapona i brojači prorade odvodnika.

Prvi rezultati praćenja pogona pokazali su da su broj i trajanje prisilnih zastoja u odnosu na prethodno razdoblje dvostruko smanjeni čime je i postignut temeljni cilj opremanja dalekovoda linijskim odvodnicima prenapona – povećanje pouzdanosti pogona i sigurnosti opskrbe električnom energijom.

outages, the number of surges, discharge currents and oscillograms of the lightning current during a period of two years.

The results of these analyses and investigation will demonstrate the efficiency of the applied configuration of line surge arresters for the protection of the transmission line from atmospheric discharges and the eventual need for the relocation of existing line surge arresters and the addition of new ones.

The oscillograms and parameters of the actual lightning currents will provide the basis for the improvement of input data and simulation using a software program for the determination of the optimal configuration of the line surge arresters, and thereby also the improvement of the efficiency of the line transmission protection from atmospheric discharges.

Based upon the results of the pilot project, a conclusion will also be reached regarding the continued application of line surge arresters for the protection of 110 kV, 220 kV and 400 kV transmission lines from atmospheric discharges in the transmission network of Croatia.

6 CONCLUSION

The 110 kV Ston – Komolac Transmission Line is particularly significant in the transmission network of Croatia due to the delivery of energy generated by the Dubrovnik Hydroelectric Power Plant to the electrical power system and the supply of electrical energy to the greater Dubrovnik region.

The route of the 110 kV Ston – Komolac Transmission Line passes through a region that has a high isokeraunic level with approximately 70 thunder days per year and frequent strong atmospheric discharges.

Therefore, in the operation of this transmission line during the period from 1995 to 2006, a large number of forced outages of long duration were recorded, which greatly exceeded the average for the transmission network of Croatia.

With the goals of providing protection from atmospheric discharges, improving operation reliability and increasing the security of the supply of electricity to the Dubrovnik region, line surge arresters and surge counters were installed on the 110 kV Ston – Komolac Transmission Line during the summer of 2007.

The initial results of the monitoring operations

Pilot projektom monitoringa pogona linijskih odvodnika prenapona DV 110 kV Ston - Komolac u nastavku je predviđeno instaliranje 2 mjerna uređaja za mjerenje i oscilografiranje oblika struja groma na stupovima u zoni najintenzivnijih atmosferskih pražnjenja te dalje praćenje i analiza broja i trajanja prisilnih zastoja i djelovanja atmosferskih pražnjenja.

Rezultati pilot projekta bit će temelj za primjenu linijskih odvodnika prenapona za zaštitu dalekovoda od atmosferskih pražnjenja i na višim naponskim razinama.

demonstrated that the number and duration of the forced outages in relation to the previous period were reduced by two-fold, thereby achieving the basic goal of increasing the security of operation and the electricity supply by equipping the transmission line with line surge arresters.

The continuation of the pilot project for the monitoring of the operation of the line surge arresters of the 110 kV Ston – Komolac Transmission Line anticipates the installation of two devices for measuring and recording lightning current waveforms at the towers in the zone of the greatest intensity of atmospheric discharges and the continued monitoring and analysis of the number and duration of forced outages and atmospheric discharges.

The results of the pilot project will provide the basis for determining the use of line surge arresters for the protection of the transmission line from atmospheric discharges at higher voltage levels.

LITERATURA / REFERENCES

- [1] Statistika pogonskih događaja u prijenosnoj mreži u 2006. godini, HEP-Operator prijenosnog sustava d.o.o., 2007.
- [2] SADOVIĆ, S., Different Line Surge Arrester Application, International Colloquium Application of Line Surge Arresters in Power Distribution and Transmission Systems, Cavtat, 2008
- [3] PUHARIĆ, M., MESIĆ, M., LOVRIĆ, M., RADOVANOVIĆ, J., SADOVIĆ, S., Lighting Performance Improvement of 123 kV Line Ston-Komolac by Use of Line Surge Arresters, International Colloquium Application of Line Surge Arresters in Power Distribution and Transmission Systems, Cavtat, 2008
- [4] BOJIĆ, S., DOLIĆ, I., SEKSO, A., RADOVANOVIĆ, J., ŠKARICA, D., First Experience in Monitoring of Line Surge Arresters Installed on 110 kV Transmission Line Ston - Komolac in Croatia, International Colloquium on Application of Line Surge Arresters in Power Distribution and Transmission Systems, Cavtat, 2008

Adresa autora:

Miroslav Mesić, dipl. ing.
miroslav.mesic@hep.hr

Dalibor Škarica, dipl. ing.
d.skarica@hep.hr

HEP-Operator prijenosnog sustava d.o.o.
Kupska 4
10000 Zagreb
Hrvatska

Dr. sc. **Milan Puharić**
milan.puharic@hera.hr

Hrvatska energetska regulatorna agencija (HERA)
Ulica grada Vukovara 14
10000 Zagreb
Hrvatska

Address of author:

Miroslav Mesić, dipl. ing.
miroslav.mesic@hep.hr

Dalibor Škarica, dipl. ing.
d.skarica@hep.hr

HEP-Operator prijenosnog sustava d.o.o.
Kupska 4
10000 Zagreb
Croatia

Milan Puharić, PhD
milan.puharic@hera.hr

Hrvatska energetska regulatorna agencija (HERA)
Ulica grada Vukovara 14
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2008-09-22

Prihvaćeno:
2008-10-02

Manuscript received on:
2008-09-22

Accepted on:
2008-10-02

NUMERIČKO RJEŠAVANJE RASPODJELE ELEKTROMAGNETSKOG I TEMPERATURNOG POLJA ZRAČNOG TRANSFORMATORA NUMERICAL SOLUTION FOR THE DISTRIBUTION OF THE ELECTROMAGNETIC AND THERMAL FIELDS OF AN AIR-CORE TRANSFORMER

Izudin Kapetanović - Nermin Sarajlić - Majda Tešanović - Mensur Kasumović, Tuzla, Bosna i Hercegovina

U radu je prikazano numeričko rješavanje raspodjele elektromagnetskog i temperaturnog polja zračnog transformatora, metodom konačnih elemenata. Raspodjela magnetskog polja određena je za magnetsko-dinamičko stacionarno stanje i magnetsku jezgru s nelinearnom karakteristikom. Predstavljeni model omogućava uspostavljanje kriterija za optimiranje rada transformatora pod različitim uvjetima opterećenja, okoliša, pa i u slučajevima kvara. Na ovaj način transformator može raditi maksimalnim kapacitetom, dok su istodobno opasnosti od kvarova zbog pregrijavanja svedene na najmanju moguću mjeru.

The article presents a numerical solution for the distribution of the electromagnetic and thermal fields of an air-core transformer using the finite element method. The distribution of the magnetic field is determined for the dynamic steady state and magnetic nonlinear core characteristics. The model presented facilitates the establishment of criteria for optimizing transformer operation under various load conditions, environments as well as in the case of failures. Thus, the transformer can operate at maximum capacity while, at the same time, the probability of faults due to overheating is reduced to a minimum.

Ključne riječi: elektromagnetsko polje; numerički proračun; temperaturno polje; zračni transformator

Key words: air-core transformer; electromagnetic field; numerical calculation; thermal field



1 UVOD

Predviđanje i određivanje elektromagnetskih i termičkih pojava u sastavnim metalnim dijelovima transformatora vrlo je važan korak u procesu projektiranja uređaja. Kvarovi transformatora uvijek uzrokuju nepovratna unutarnja oštećenja. Osnovni kriterij koji ograničava mogućnost opterećenja transformatora i njegov životni vijek djelimično je određen sposobnošću transformatora da disipira toplinu, generiranu u svojoj unutrašnjosti u okolni prostor.

Stoga je od velike važnosti predviđanje termičkog ponašanja transformatora tijekom normalnog opterećenja. Kreiranje modela transformatora vrlo je važno za proces monitoringa rada transformatora. Za numeričko rješavanje raspodjele elektromagnetskog i temperaturnog polja korišten je laboratorijski zračni transformator. Rezultati dobiveni numeričkim proračunom u idućem poglavlju uspoređeni su s rezultatima dobivenim u laboratorijskim mjerenjima.

Podaci o transformatoru su:

- tip DP/0-9896,
- nominalna snaga 2,4 kVA,
- nominalni napon, namot visokog napona (VN) 500 V,
- nominalni napon, namot niskog napona (NN) 380 V,
- frekvencija 50 Hz,
- nominalna primarna struja 3 A,
- nominalna sekundarna struja 3,6 A,

2 MATEMATIČKI MODEL MAGNETSKOG I TOPLINSKOG POLJA

Izvori elektromagnetskog i toplinskog polja su struje koje teku kroz namote transformatora, odnosno Jouleovi gubici koji nastaju kao posljedica protjecanja struja kroz vodiče, tj. namote transformatora.

Elektromagnetsko polje je određeno jednačinama:

$$\nabla \times \mathbf{H} = \sigma(T)\mathbf{E} \quad (1a)$$

$$\nabla \times \mathbf{H} = \sigma(T)\mathbf{E} \quad (1b)$$

$$\nabla \cdot [\mu(H, T)\mathbf{H}] = 0 \quad (1c)$$

$$\nabla \times \mathbf{E} = -\frac{\partial [\mu(H, T)\mathbf{H}]}{\partial t} \quad (1d)$$

1 INTRODUCTION

The prediction and determination of electromagnetic and thermal phenomena in the metal parts of transformers are very important steps in the process of designing equipment. Transformer faults always cause internal damage. The basic criterion that limits transformer loading and its lifetime is partially determined by the ability of the transformer to dissipate internally generated heat into the surrounding area.

Therefore, it is of great importance to predict the thermal behavior of a transformer under normal load. Creating a transformer model is very important for the process of monitoring transformer operation. Laboratory air-core transformer data were used for the numerical determination of the distribution of the electromagnetic and temperature fields. The results obtained from the numerical calculation in the next chapter have been compared to the results obtained from laboratory measurements.

The transformer data are as follows:

- type DP/0-9896,
- nominal power 2,4 kVA
- nominal voltage, high voltage winding (HV) 500 V
- nominal voltage, low voltage winding (LV) 380 V
- frequency 50 Hz
- nominal primary current 3 A
- nominal secondary current 3,6 A

2 MATHEMATICAL MODEL OF ELECTROMAGNETIC AND THERMAL FIELDS

The sources of electromagnetic and thermal fields are currents that flow through transformer windings, i.e. joule losses that occur in consequence of the current flowing through conductors, i.e. transformer windings.

An electromagnetic field is determined by the following equation:

Ukupna gustoća struje određena je jednadžbom:

Total current density is determined by the following equation:

$$\mathbf{J}_{\text{uk}} = \mathbf{J}_{\text{iz}} + \sigma(T) \frac{d\mathbf{A}}{dT} = \sigma(T) \left(\mathbf{E}_{\text{iz}} + \frac{\partial \mathbf{A}}{\partial t} \right) \quad (2)$$

Toplinsko polje je opisano jednadžbom:

A thermal field is described by the following equation:

$$\nabla(\lambda \nabla T) - \rho c \frac{\partial T}{\partial t} + q_v = 0, \quad (3)$$

i predstavlja diferencijalnu jednadžbu nestacionarnog prijenosa topline, u kojoj je:

and represents the differential equation of non-steady state heat transfer, in which:

T - tražena funkcija raspodjele temperature u prostoru i vremenu [K],
 c - specifični toplinski kapacitet [J/kg·K],
 ρ - specifična gustoća materijala [kg/m³],
 λ - koeficijent vođenja topline [W/m·K],
 q_v - toplinska izdašnost eventualnog izvora topline u promatranoj točki,
 t - vrijeme [s],

T - the sought function of temperature distribution in space and time [K]
 c - the specific heat capacity [J/kg·K]
 ρ - the specific material density [kg/m³]
 λ - the coefficient of thermal conductivity [W/m·K]
 q_v - heat generation of the eventual heat source at the observed point [J]
 t - time [s],

pri čemu su to funkcije prostora i temperature.

where the above are functions of space and temperature.

Razmjena topline između površina vodiča, jezgre, ulja i okolnog zraka dana je jednadžbom:

Heat exchange among the surfaces of the conductor, core, oil and ambient air are given in the following equation:

$$-\lambda \frac{\partial T}{\partial t} = \alpha(T_p - T_f) \quad (4)$$

Za rješavanje diferencijalnih jednadžbi kod zadanih početnih i graničnih uvjeta korištena je metoda konačnih elemenata (MKE). MKE je aproksimativni postupak. Primjenom ove metode problem rješavanja parcijalne diferencijalne jednadžbe prijelaza topline svodi se na rješavanje sustava simultanih linearnih jednadžbi. Područje unutar kojeg se rješava problem dijeli se na konačan broj elemenata. Kao rješenje dobivaju se temperature u čvorištima elemenata, dok se temperature unutar elemenata aproksimiraju pomoću vrijednosti u čvorištima elemenata.

For the solution of differential equations with the given initial and final conditions, the finite element method (FEM) was used. FEM is an approximate procedure. By applying this method, the problem of solving the partial differential equation of heat transfer is reduced to the solution of a system of simultaneous linear equations. The region within which the problem is solved is divided into a finite number of elements. The temperatures of the element nodes are obtained as solutions, while the temperatures within the elements are approximated using the values of the element nodes.

3 MODEL ZRAČNOG TRANSFORMATORA

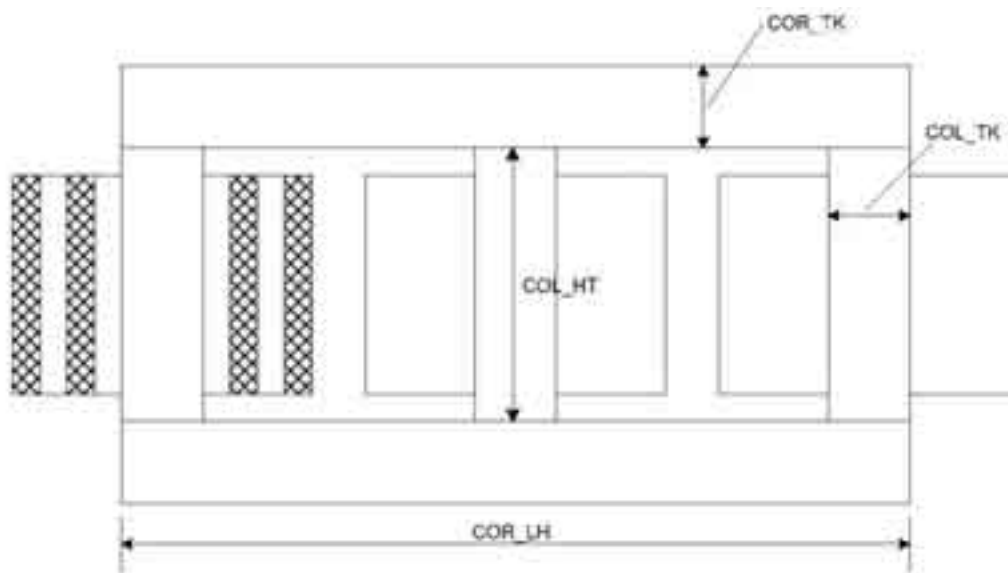
3 AIR-CORE TRANSFORMER MODEL

Za proračun elektromagnetskog i temperaturnog polja trofaznog zračnog energetskog transformatora metodom konačnih elemenata korišten je programski paket FLUX2D.

For the calculation of the electromagnetic and thermal fields of a three-phase air-core power transformer using the finite element method, the software program FLUX2D was employed.

Proračun temperaturnog polja vršen je u poprečnom presjeku transformatora u dvije

Two-dimensional calculation of the thermal field in the cross section of the transformer was performed.



Slika 1 – Geometrija transformatora
Figure 1 – Transformer geometry

dimenzije. Cilj je bio dobiti model trofaznog zračnog energetskog transformatora koji bi što vjernije prikazao zagrijavanja i raspodjelu temperatura, koje se javljaju pri radu transformatora.

Da bi se moglo izvršiti modeliranje termičkih procesa transformatora potrebno je primijeniti složeni matematički model koji opisuje spregnuta elektromagnetska i temperaturna polja. Pokazani model zračnog transformatora napravljen je s ciljem dobivanja informacije o stanju transformatora.

Na slici 1 prikazana je geometrija analiziranog transformatora. U tablici 1 dani su podaci o geometriji korištenog zračnog transformatora.

The goal was to obtain a model of a three-phase air-core power transformer that would describe the heating and temperature distribution which occur during transformer operation as accurately as possible.

In order to model the thermal processes of a transformer, it is necessary to apply a complex mathematical model that describes coupled electromagnetic and thermal fields.

The model of the air-core transformer presented was devised with the goal of obtaining information on the state of the transformer.

In Figure 1, the geometry of the analyzed transformer is presented. In Table 1, data are presented on the geometry of the air-core transformer used.

Tablica 1 – Podaci o geometriji transformatora
Table 1 – Data on the transformer geometry

Parametar / Parameter	Opis / Description	Veličina / Value [mm]
COL_HT	Visina stupa / Leg height	145
COR_TK	Debljina gornjeg i donjeg dijela jezgre / Top and bottom yolk thickness	50
COL_TK	Debljina stupa / Leg thickness	30
COR_LH	Dužina jezgre / Core leg	250
INS_TK	Debljina izolacije / Insulation thickness	7
C1_TK	Debljina namota 1 / Thickness of Winding 1	7,5
C2_TK	Debljina namota 2 / Thickness of Winding 2	7,5
COIL_HT	Visina namota / Winding height	145
R_INT	Unutrašnji promjer domena proračuna / Internal diameter of the calculation domains	2 000
R_EXT	Vanjski promjer domena proračuna / External diameter of the calculation domains	2 300

Ovaj model pruža važne informacije koje karakteriziraju termičke procese važne za prognozu, simuliranje i analiziranje rada transformatora.

Inače, fenomeni koji se događaju u električnim uređajima opisani su diferencijalnim jednačinama:

- Maxwellovim jednačinama,
- toplinskim jednačinama,
- zakonitostima o ponašanju materijala.

Do jednostavnog rješenja ovih jednačini nije moguće doći zbog poteškoća koje su posljedica kompleksnosti jednačina i velikog broja proračuna koji se moraju izvršiti. Zbog toga, moduli fizikalne aplikacije koje nudi FLUX2D dopuštaju rješenje bilo kojeg zadanog problema, opisanog jednačinom i hipotezama.

Tako se npr. transformator može proučavati na dva načina:

- kao magnetski problem (ako se žele odrediti Jouleovi gubitci) i
- kao električni problem (ako se želi znati vjerojatnost ispada transformatora).

Stoga ga je nužno analizirati posebno s magnetodinamičkom aplikacijom, a posebno s elektrostatičkom aplikacijom.

Problemi magnetske prirode mogu se analizirati sa sljedećim fizikalnim aplikacijama:

- magnetostatičkom,
- magnetodinamičkom,
- elektrodinamičkom,
- aplikacijom za tranzijentna stanja u magnetizmu,
- aplikacijom za proučavanje uređaja s pokretnim dijelovima koji se kreću translatorno ili rotacijski,
- aplikacijom koja se odnosi na supervodičke pojave,
- aplikacijom koja uzima u obzir i vanjske električne krugove,
- aksiperiodičnom aplikacijom.

Problemi termičke prirode mogu se rješavati primjenom aplikacije za:

- stacionarna termička stanja,
- tranzijentna termička stanja,
- magnetotermičke probleme,
- elektrotermičke probleme,
- dielektrotermičke probleme.

Elektromagnetsko polje je proračunato korištenjem magnetodinamičkog modela. Pro-

This model provides important information that characterizes the thermal processes necessary for the prediction, simulation and analysis of transformer operation.

The phenomena that occur in electrical equipment are described by the following differential equations:

- Maxwell's equations,
- thermal equations, and
- material behavior laws.

It is not possible to arrive at simpler solutions to these equations due to the complexity of the equations and the large number of calculations that must be performed. Therefore, the physical application models offered by FLUX2D facilitate solutions to any given problem, described by an equation and hypotheses.

Thus, for example, a transformer may be studied in two ways:

- as a magnetic problem, in order to determine Joule losses, and
- as an electrical problem, (in order to determine the probability of transformer failure).

Therefore, the transformer must be separately analyzed by a magnetodynamic application and an electrostatic application.

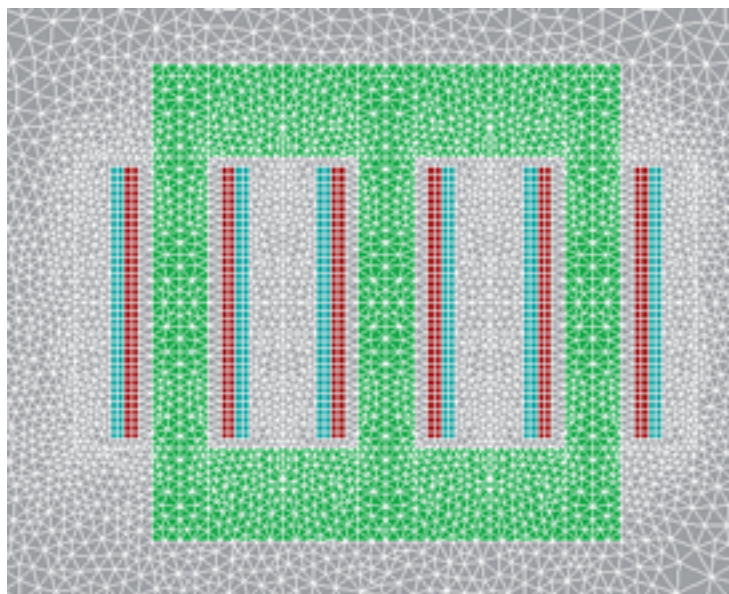
Problems of a magnetic nature may be analyzed using the following physical applications:

- magnetostatic,
- magnetodynamic,
- electrodynamic,
- an application for transient magnetic states,
- an application for studying equipment with parts that move translationally or rotationally,
- an application that refers to superconductive phenomena,
- an application that also takes external electrical circuits into account, and
- an aperiodic application.

Problems of a thermal nature can be solved using applications for the following:

- steady thermal states,
- transient thermal states,
- magnetothermal problems,
- electrothermal problems, and
- dielectric thermal problems.

An electromagnetic field is calculated using a magnetodynamic model. By studying the



Slika 2 – Mreža konačnih elemenata
Figure 2 – Network of finite elements

matranim termičkim problemom također se definira područje proračuna kojem pripada. U analiziranom slučaju to je područje tranzijentno termičkog proračuna.

Transformator koji je u ovom radu analiziran sadrži magnetske materijale s nelinearnom permeabilnosti u željeznoj jezgri.

Kreirani model transformatora sadrži 34 729 čvornih točaka i 16 495 trokutastih elemenata (slike 2 i 3).

Kvaliteta mreže opisana je sljedećim podacima:

- broj elemenata dobre kvalitete: 99,01 %,
- broj elemenata osrednje kvalitete: 0,97 %,
- broj elemenata lošije kvalitete: 0,02 %.

thermal problem, the corresponding area of calculation is also defined. In the case analyzed, this is the area of a transient thermal calculation.

The iron core of the transformer analyzed in this article consists of magnetic materials with nonlinear permeability.

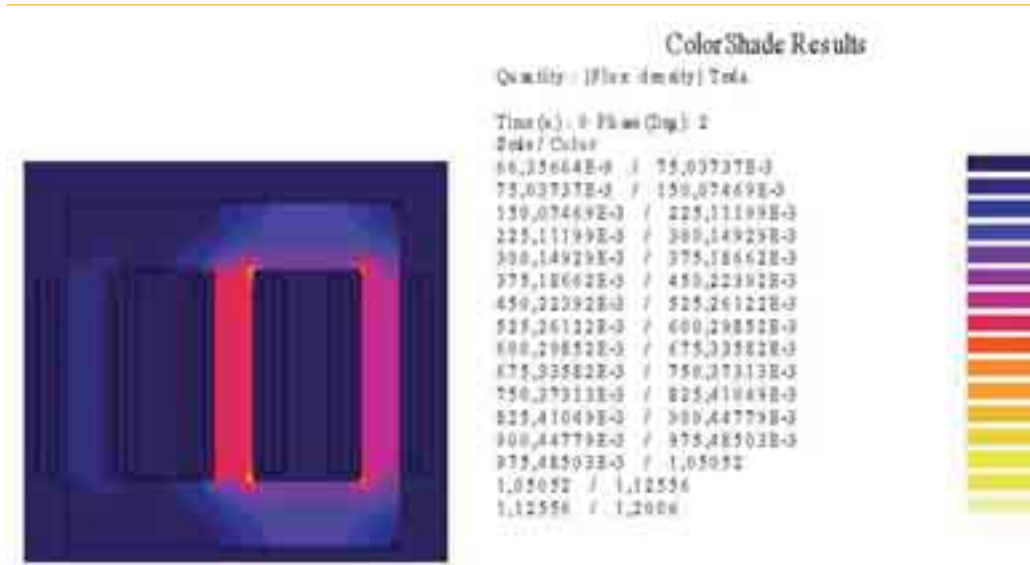
The transformer model created consists of 34 729 nodal points and 16 495 triangular elements (Figures 2 and 3).

The quality of the network is described by the following data:

- the number of good quality elements: 99,01 %,
- the number of medium quality elements: 0,97 %, and
- the number of poor quality elements: 0,02 %.

00:09:46	126 sec.	1812 1 st order lineic elements created
00:09:47	126 sec.	Display of 71 faces....
00:09:48	128 sec.	Finished updating display
00:09:48	128 sec.	Generating 2 nd order elements is running
00:09:49	128 sec.	End generating 2 nd order elements
Total number of nodes → 34 729		
Number of elements not evaluated		: 0 %
Number of good quality elements		: 99,01 %
Number of medium quality elements		: 0,97 %
Number of poor quality elements		: 0,02 %
Number of bad quality elements		: 0 %

Slika 3 – Podaci o kvaliteti mreže konačnih elemenata
Figure 3 – Data on the quality of the network of finite elements



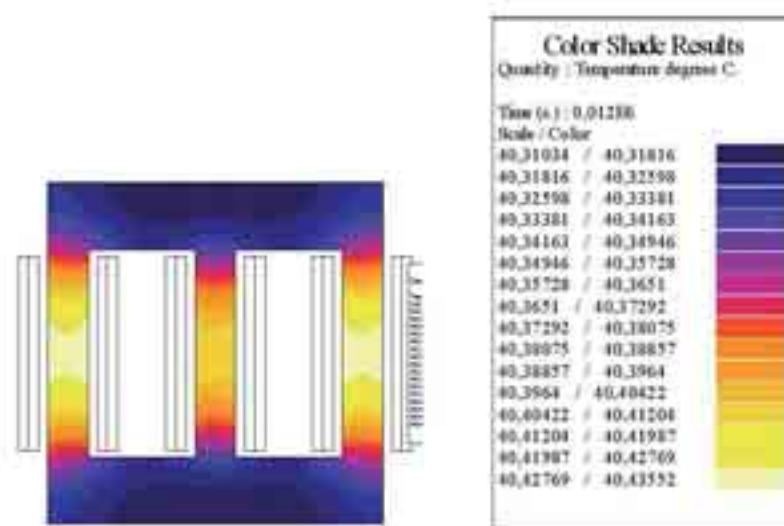
Slika 4 – Magnetska indukcija (fazni kut 0 stupnjeva)
Figure 4 – Magnetic induction (phase angle 0 degrees)

4 NUMERIČKI PRORAČUN ELEKTROMAGNETNOG I TEMPERATURNOG POLJA ZRAČNOG TRANSFORMATORA

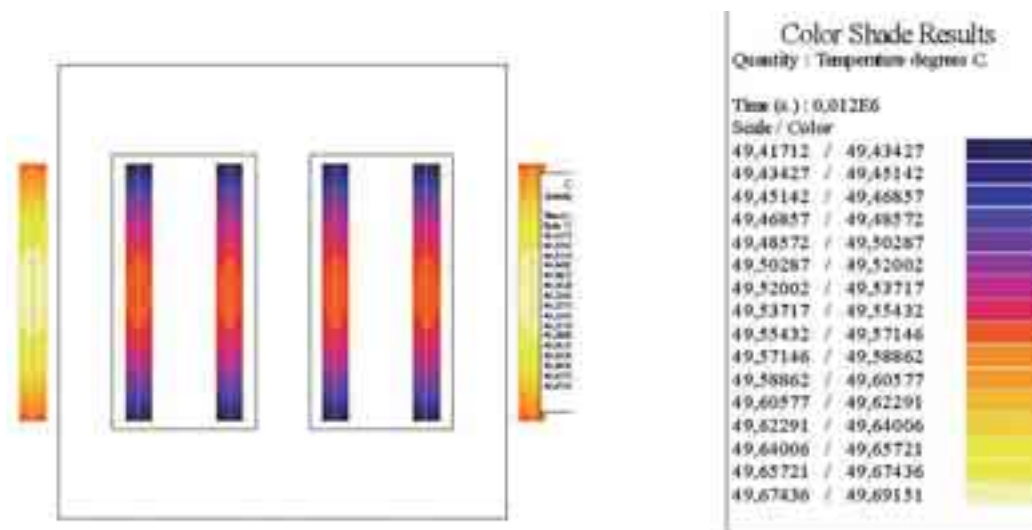
Numerički proračun vršen je na sljedeći način: izvori elektromagnetnog i temperaturnog polja struje su koje teku namote transformatora, odnosno Jouleovi gubitci koji nastaju kao posljedica protjecanja struja kroz vodiče, tj. namote transformatora.

4 NUMERICAL CALCULATION OF THE ELECTROMAGNETIC AND THERMAL FIELDS OF THE AIR-CORE TRANSFORMER

The numerical calculation is performed as follows: The sources of the electromagnetic and thermal fields are the currents that flow through the transformer windings, i.e. Joule losses that occur due to current flow through conductors, i.e. transformer windings.



Slika 5 – Raspodjela temperature u jezgri trofaznog zračnog transformatora nakon 12 000 sekundi
Figure 5 – Temperature distribution in the core of the three-phase air-core transformer after 12 000 seconds



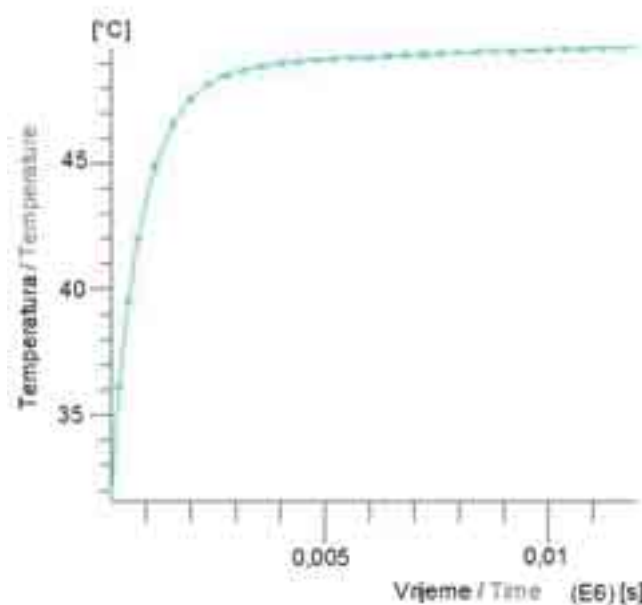
Slika 6 – Raspodjela temperature u namotima trofaznog zračnog transformatora nakon 12 000 sekundi
 Figure 6 – Temperature distribution in the windings of the three-phase air-core transformer after 12 000 seconds

Rezultati raspodjele magnetskog i temperaturnog polja u poprečnom presjeku trofaznog zračnog transformatora prikazani su na slikama 4, 5 i 6.

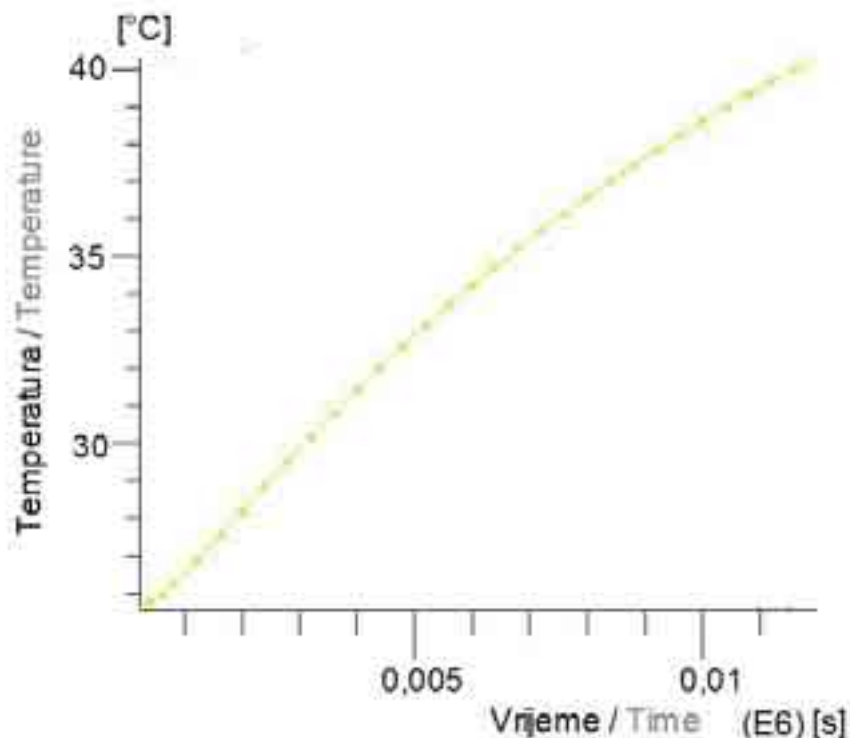
The results of the distribution of the magnetic and thermal fields in the cross-sectional area of the three-phase air-core transformer are presented in Figures 4, 5 and 6.

Na slici 5 prikazana je raspodjela temperature u jezgri trofaznog zračnog transformatora, za vremensko razdoblje od 12 000 sekundi nakon priključenja transformatora na mrežu.

In Figure 5, the temperature distribution in the core of the three-phase air-core transformer for the time period of 12 000 seconds after the connection of the transformer to the network is presented.



Slika 7 – Temperatura u točki na sredini namota čije su koordinate (-146,524, -1,254), nakon 12 000 sekundi
 Figure 7 – Temperature at a point in the center of the winding [coordinates: -146,524, -1,254], after 12 000 seconds



Slika 8 – Temperatura u točki na sredini jezgra čije su koordinate [1,568, 128,012], nakon 12 000 sekundi
 Figure 8 – Temperature at a point in the center of the core, [coordinates: -1,568, 128,012], after 12 000 seconds

Na slici 6 je prikazana raspodjela temperature u namotima trofaznog zračnog transformatora, za vremensko razdoblje od 12 000 sekundi.

Na slikama 7 i 8 prikazani su dijagrami promjene temperature u vremenu od 12 000 s u točki u centru namota i jezgri.

4.1 Laboratorijska mjerenja

S obzirom da se radi o zračnom transformatoru, mjerenja temperature mogla su se izvršiti termometrima. Kod ovih transformatora razlika između prosječne temperature namota i lokalnih temperatura nije velika. Mjerenje je izvršeno na najtoplijem pristupačnom mjestu namota. Temperatura vanjskog dijela željezne jezgre kod suhih transformatora također se može mjeriti termometrom. Kao temperatura rashladnog sredstva, u ovom slučaju mjerena je temperatura okolnog zraka, na udaljenosti 1 m do 2 m od transformatora, i u polovici njegove visine. Termometri su bili zaklonjeni od strujanja i izjaravanja. Transformator je bio opterećen otpornikom otpornosti od $R_{opt} = 29 \Omega$, simetrično u sve tri faze.

In Figure 6, the temperature distribution in the windings of the three-phase air-core transformer for the time period of 12 000 seconds is presented.

In Figures 7 and 8, charts are presented of the changes in temperature during a time period of 12 000 s at a point in the center of the winding and core.

4.1 Laboratory measurements

Since this concerns an air-core transformer, temperature measurements can be performed with a thermometer. For these transformers, the difference between the average winding temperature and the ambient temperature is not great. Measurement was performed at the hottest accessible spot of the winding. The temperature of the external part of the iron core for dry transformers may also be measured by a thermometer. The temperature of the cooling agent, in this case the temperature of the ambient air, was measured at a distance of 1 m to 2 m from the transformer, at half of its height. The thermometers were protected from air flow and radiation. The transformer was loaded with a resistive load, $R_{opt} = 29 \Omega$, symmetrical in all three phases.

Fazni naponi primarnog i sekundarnog namota tijekom izvođenja eksperimenta bili su:

$$U_{\text{prim},f} = 176 \text{ V},$$

$$U_{\text{sek},f} = 143 \text{ V}.$$

Struje koje su protjecale kroz namote primara i sekundara bile su:

$$I_{\text{prim}} = 2,8 \text{ A},$$

$$I_{\text{sek}} = 3,6 \text{ A}.$$

Izmjerena temperatura okoline na početku mjerenja je bila 25,5 °C, temperatura jezgre 22,2 °C, a temperatura namota 25,5 °C. Mjerenje je započelo u 11:35 sati, a očitavanje pokazivanja dviju sonde postavljenih na namot i jezgru vršeno je svakih deset minuta, sve dok temperatura namota nije postala stalna, tj. dok nije nastupilo stacionarno stanje. Mjerenje je trajalo 3 sata i 20 minuta.

Rezultati mjerenja dani su u tablici 2.

The phase voltages of the primary and secondary windings during the experiment were as follows:

$$U_{\text{prim},f} = 176 \text{ V},$$

$$U_{\text{sek},f} = 143 \text{ V}.$$

The currents that passed through the primary and secondary windings were as follows:

$$I_{\text{prim}} = 2,8 \text{ A},$$

$$I_{\text{sek}} = 3,6 \text{ A}.$$

The measured ambient temperature at the beginning of measurement was 25,5° C, the core temperature was 22,2° C, and the winding temperature 25,5° C. Measurement began at 11:35 a.m. and readings of two probes placed on the winding and core were performed every ten minutes, until the temperature of the windings became constant, i.e. until steady state was reached. Measurement lasted for 3 hours and 20 minutes.

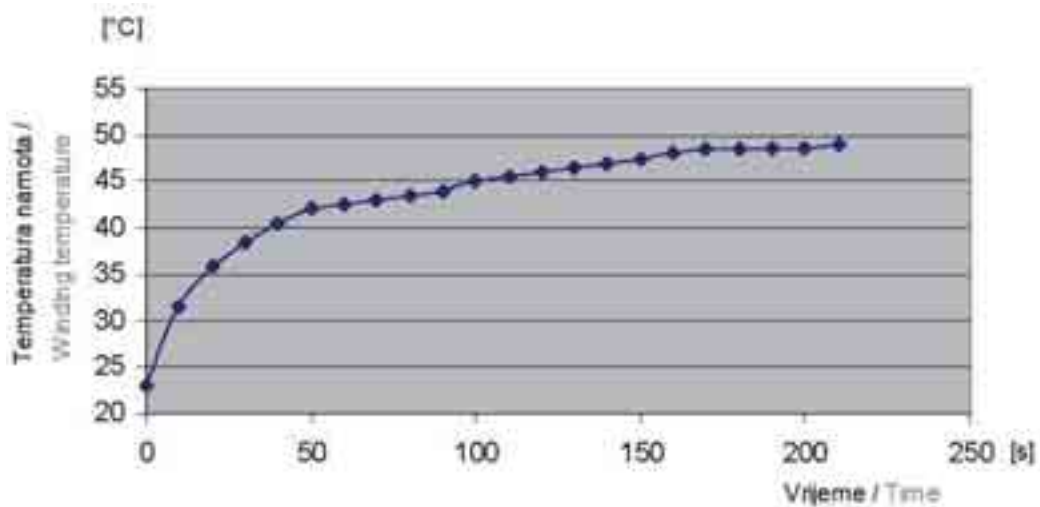
The results of the measurement are presented in Table 2.

Tablica 2 — Rezultati mjerenja temperatura jezgre i namota
Table 2 — The results of the measurements of the core and winding temperatures

Vrijeme mjerenja [sati] / Time of measurement	11:45	11:55	12:05	12:15	12:25	12:35	12:45	12:55	13:05
Temperatura jezgre / Core temperature [°C]	23	23,95	24,9	26,0	27,2	28,3	29,4	30,5	31,6
Temperatura namota / Winding temperature [°C]	31,5	36,0	38,5	40,5	42,0	42,5	43,0	43,5	44,0

Vrijeme mjerenja [sati] / Time of measurement	13:15	13:25	13:35	13:45	13:55	14:05	14:15	14:25	14:35
Temperatura jezgre / Core temperature [°C]	32,6	33,5	34,5	35,3	36,0	36,8	37,5	38,2	38,8
Temperatura namota / Winding temperature [°C]	45,0	45,5	46,0	46,5	47,0	47,5	48,0	48,5	48,5

Vrijeme mjerenja [sati] / Time of measurement	14:45	14:55	15:05
Temperatura jezgre / Core temperature [°C]	39,4	39,9	40,4
Temperatura namota / Winding temperature [°C]	48,5	48,5	49,0



Slika 9 – Promjena temperature namota u vremenu
Figure 9 – Changes in winding temperature over time

Tablični rezultati prikazani su na slikama 9 i 10, pomoću dijagrama.

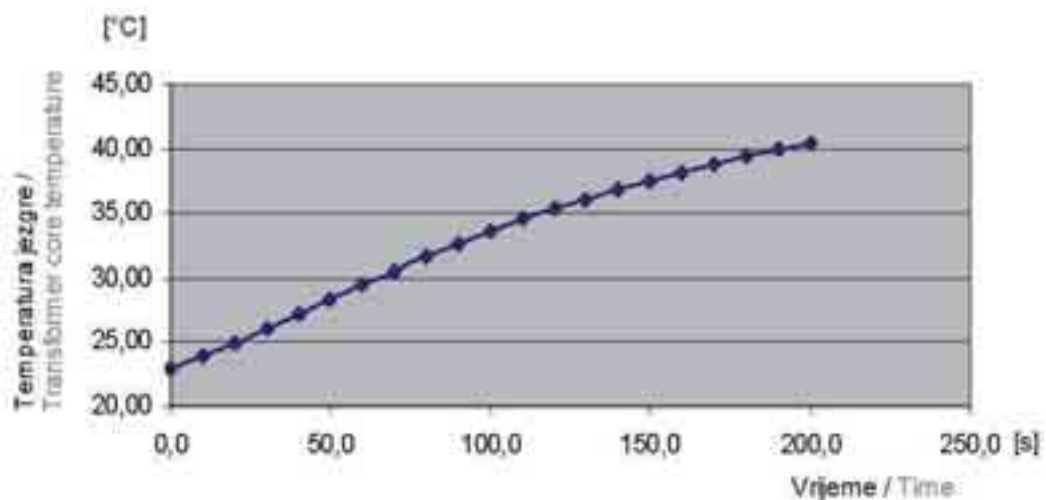
The results are presented in Figures 9 and 10.

5 ZAKLJUČAK

Analizom dobivenih rezultata numeričkog proračuna: raspodjele magnetske indukcije, raspodjele silnica magnetskog polja, temperaturnog polja u poprečnom presjeku trofaznog zračnog transformatora, kao i dijagrama promjene temperature u pojedinim točkama u vremenskom razdoblju od 12 000 sekundi, može se zaključiti:

5 CONCLUSION

Through analysis of the results obtained by numerical calculation, the distribution of magnetic induction, the distribution of magnetic field lines, the temperature field in the cross-sectional area of the three-phase air-core transformer, as well as the temperature change charts for individual points during a time period of 12 000 seconds, the following can be concluded:



Slika 10 – Promjena temperature jezgra u vremenu
Figure 10 – Changes in core temperature over time

- Na slici 4 prikazana je raspodjela magnet-ske indukcije u jezgri trofaznog zračnog transformatora. Srednja vrijednost magnet-ske indukcije dobivena iz rezultata numeričkog proračuna, a koji predstavljaju vrijednosti magnetne indukcije u srednjem stupu jezgre, iznosi približno 0,5 mT, što odgovara vrijednosti magnetske indukcije izmjerenoj pomoću Hall-ove sonde postavljene na mjesto između 2 stupa, a koja iznosi 0,46 mT.
- Na slici 5 prikazan je dijagram promjene temperature u određenim točkama (danim određenim koordinatama) jezgre. Za proračun je uzeta temperatura okoline od 25,5 °C, što odgovara temperaturi pri izvođenju laboratorijskog eksperimenta.
- Na slici 6 prikazana je raspodjela temperature u trofaznom zračnom energetskom transformatoru. Najtopliji su namoti, gdje temperature dosežu maksimalnu vrijednost od 49,69 °C. Prema rezultatima provedenog eksperimenta, maksimalna izmjerena vrijednost temperature namota iznosila je 49 °C. To znači da su vrijednosti dobivene eksperimentalnim i numeričkim putem približno iste.
- Pri ustaljenom radnom stanju zračnog transformatora mehanizam hlađenja je sljedeći: zrak dodiruje aktivne dijelove transformatora u kojima se proizvode gubitci čija je temperatura najviša. Zbog toga se dodirni zrak zagrijava, postaje lakši i ide naviše, na njegovo mjesto dolazi donji hladniji zrak i na taj način se ostvaruje prirodna cirkulacija zraka. Međutim, pri stacionarnom stanju (ustaljenom opterećenju, npr. nominalnom), temperature pojedinih dijelova transformatora u zavisnosti od njegove visine, nisu jednake. Najviše se zagrijavaju namoti, zatim magnetski krug pa okolni zrak.
- Kada se izvodi pokus zagrijavanja, pokus se prekida kada transformator dođe u stacionarno stanje, tj. kada mu je temperatura tolika da je toplina predana hlađenjem upravo jednaka razvijenoj toplini u istom vremenskom intervalu. Smatra se da je to stanje dosegnuto kad temperatura namota u zadnja dva sata ne poraste više od 1 °C. U numeričkom proračunu vrijeme trajanja proračuna je 12 000 sekundi, jer je to bilo dovoljno dugo
- In Figure 4, the distribution of the magnetic induction in the core of a three-phase air-core transformer is presented. The mean value of the magnetic induction obtained from the result of the numerical calculation, which represents the values of magnetic induction in the central leg of the core, amounts to approximately 0,5 mT, corresponding to the values of the magnetic induction measured using a Hall probe placed between two legs, which amount to 0,46 mT.
- In Figure 5, temperature changes of the core at specific points (with assigned specific coordinates) are presented. In the calculation, the ambient temperature of 25,5 °C was used, which corresponds to the temperature while the laboratory experiment was being conducted.
- In Figure 6, temperature distribution in the three-phase air-core power transformer is shown. The hottest spot of the windings reached a maximum temperature of 49,69 °C. According to the results of the experiment, the maximum measured value of the winding temperature was 49 °C. This means that the values obtained experimentally and numerically are approximately the same.
- Under steady state conditions, the cooling mechanism of the air-core transformer is as follows: air comes into contact with the active parts of the transformer in which losses are generated and which have the highest temperatures. Therefore, the air in contact with the hot surface heats up, becomes lighter and rises upwards. It is replaced by colder lower air, thereby creating natural air circulation. However, during steady state conditions (steady load, e.g. nominal load), the temperatures of the individual parts of the transformer are not equal, depending upon their heights. The windings heat up the most, followed by the magnetic circuit and then the ambient air.
- While the heating experiment is being conducted, it is interrupted when the transformer reaches the steady state, i.e. when its temperature is so high that heat transferred by cooling is actually equal to the generated heat during the same time interval. It is believed that this state is reached when the winding temperature has not increased by more than 1 °C during the preceding two hours. In the numerical calculation, the duration of the calculation is 12 000 seconds, because this is a time period long enough to include the steady state as well, i.e. the temperature of the transformer winding had become steady.

vremensko razdoblje da se njime obuhvati i stacionarno stanje, tj. temperatura namota transformatora je postala stalna.

Zagrijavanje transformatora, ako se zanemare prijelazne pojave između bakra (aluminija) i zraka, i ako se transformator promatra kao homogeno tijelo, u kojem se razvija toplina, odvija se po eksponencijalnoj funkciji. Mjereno zagrijavanje tijekom numeričkog proračuna, u zavisnosti od vremena, predstavljeno je na dijagramima, slike 7 i 8. Može se primijetiti da se najbrže zagrijavaju namoti i da najbrže postižu stacionarno stanje. Sporiji odziv na zagrijavanje ima jezgra, kojoj treba znatno duže vrijeme da uđe u stacionarno stanje.

Točnost rezultata dobivenih numeričkim proračunom potvrđena je rezultatima eksperimentalnih mjerenja, prikazanim na slikama 9 i 10. Usporedbom dijagrama prikazanih na slikama 7 i 8, koji su rezultat numeričkog proračuna i dijagrama prikazanih na slikama 9 i 10, koji su rezultat eksperimentalnih mjerenja, može se primijetiti da su približno jednaki, što ukazuje na opravdanost uvođenja i razvijanja ovakvih numeričkih proračuna za praktične probleme.

Postotna pogreška između mjerenih i proračunatih vrijednosti, za trofazni zračni transformator određena je na sljedeći način:

Temperature namota i jezgre dobivene numeričkim proračunom i mjerenjem, u stacionarnom stanju iznose:

$$\begin{aligned} T_{n,np} &= 49,69 \text{ }^{\circ}\text{C}, \\ T_{n,mj} &= 49 \text{ }^{\circ}\text{C}, \\ T_{j,np} &= 41 \text{ }^{\circ}\text{C}, \\ T_{j,mj} &= 40,4 \text{ }^{\circ}\text{C} \end{aligned}$$

gdje je:

$T_{n,np}$ - temperatura namota dobivena numeričkim proračunom,
 $T_{n,mj}$ - temperatura namota izmjerena,
 $T_{j,np}$ - temperatura jezgre dobivena numeričkim proračunom,
 $T_{j,mj}$ - temperatura jezgre izmjerena.

Apsolutna pogreška je:

$$\begin{aligned} \Delta T_n &= 49,69 - 49 = 0,69 \text{ }^{\circ}\text{C} \\ \Delta T_j &= 41,0 - 40,4 = 0,6 \text{ }^{\circ}\text{C} \end{aligned}$$

gdje je:

T_n - temperatura namota,
 T_j - temperatura jezgre.

The heating of the transformer occurs according to exponential function if transient phenomena are ignored between copper (aluminum) and the air, and if the transformer is viewed as a homogeneous body in which heat is generated. Temperature as a function of time is presented in Figures 7 and 8. It can be noted that the windings heat and reach steady state most rapidly. The core has a slower heating response, requiring a significantly longer period of time to reach steady state.

The precision of the results obtained by numerical calculation is confirmed by the results of experimental measurements, presented in Figures 9 and 10. By comparing the charts presented in Figures 7 and 8, which are the results of numerical calculations, and the charts presented in Figures 9 and 10, which are the results of experimental measurements, it can be noted that they are approximately identical, thereby providing justification for the introduction and development of such numerical calculations for practical purposes.

The percentage of error between the measured and calculated values for the three-phase air-core transformer is determined in the following manner:

The temperatures of the windings and core obtained by numerical calculation and measurement in steady state are as follows:

$$\begin{aligned} T_{n,np} &= 49,69 \text{ }^{\circ}\text{C}, \\ T_{n,mj} &= 49 \text{ }^{\circ}\text{C}, \\ T_{j,np} &= 41 \text{ }^{\circ}\text{C}, \\ T_{j,mj} &= 40,4 \text{ }^{\circ}\text{C} \end{aligned}$$

where:

$T_{n,np}$ - winding temperature obtained by numerical calculation,
 $T_{n,mj}$ - measured winding temperature,
 $T_{j,np}$ - core temperature obtained by numerical calculation,
 $T_{j,mj}$ - measured core temperature.

The absolute error is as follows:

$$\begin{aligned} \Delta T_n &= 49,69 - 49 = 0,69 \text{ }^{\circ}\text{C} \\ \Delta T_j &= 41,0 - 40,4 = 0,6 \text{ }^{\circ}\text{C} \end{aligned}$$

where:

T_n - winding temperature,
 T_j - core temperature.

Relativna – postotna pogreška je:

$$\partial T_n = \frac{\Delta T_n}{T_{mj}} 100 = \frac{0,69}{49} 100 = 1,408 \%,$$

$$\partial T_j = \frac{\Delta T_j}{T_j} 100 = \frac{0,6}{40,4} 100 = 1,485 \%,$$

gdje je:

T_n - temperatura namota,

T_j - temperatura jezgre,

T_{mj} - izmjerena temperatura.

Ovo je pogotovo praktično s ekonomske točke gledišta, budući da se na ovaj način, tj. primjenom adekvatnih programskih paketa (npr. FLUX2D, FLUX3D) može realizirati model bilo kojeg uređaja, pa i transformatora, i na taj način reducirati potreba za eksperimentalnim skupim mjerenjima i remontima.

The relative percentage error is as follows:

$$\partial T_n = \frac{\Delta T_n}{T_{mj}} 100 = \frac{0,69}{49} 100 = 1,408 \%,$$

$$\partial T_j = \frac{\Delta T_j}{T_j} 100 = \frac{0,6}{40,4} 100 = 1,485 \%,$$

where:

T_n - winding temperature,

T_j - core temperature,

T_{mj} - measured temperature.

This is particularly practical from the economic point of view since in this manner, i.e. by using suitable software programs (e.g. FLUX2D, FLUX3D) it is possible to devise a model of any device whatsoever, including a transformer, and in this way reduce the need for expensive experimental measurements and repairs.

LITERATURA / REFERENCES

- [1] Suša, D., Lehtonen, M., Nordman, H., Dynamic Thermal Modelling of Power Transformers, IEEE Transactions on Power Delivery, Vol. 20, No.1, 2005
- [2] Šušnjić, L., Haznadar, Z., Valković, Z., Electromagnetic Analysis Applied to the Prediction of Stray Losses in Power Transformer, ICEM 16th International Conference on Electrical Machines (Book of Digests vol. 3), Krakow, 2004
- [3] Šušnjić, L., Haznadar, Z., Valković, Z., Prediction of Stray Losses in Power Transformer, ISEF 2005 – XII International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, Baiona, Spain, 2005
- [4] Haznadar, Z., Kapetanović, I., Sarajlić, N., Numerički proračun temperaturnog polja sistema generatorskih ekraniziranih sabirnica metodom konačnih elemenata, V savjetovanje BHK CIGRE, Neum, 2001.
- [5] J. Driesen, Deliege, G., Belmans, R., Hameyer, K., Coupled Thermo-Magnetic Simulation of a Foil-Winding Transformer Connected to a Nonlinear Load, IEEE Transactions on Magnetics, Vol. 36, No. 4, 2000
- [6] FLUX2D, Version 7.60: CAD Package for Electromagnetic and Thermal Analysis Using Finite Elements, CEDRAT, France, 2001

Adresa autora: Address of author:

Prof. dr. sc. Izudin Kapetanović	Prof. Izudin Kapetanović , PhD
Dr. sc. Nermin Sarajlić	Nermin Sarajlić , PhD
Mr. sc. Majda Tešanović	Majda Tešanović , MSc
Mr. sc. Mensur Kasumović	Mensur Kasumović , MSc
mensur.kasumovic@untz.ba	mensur.kasumovic@untz.ba
Univerzitet u Tuzli	University of Tuzla
Fakultet elektrotehnike	Faculty of Electrical Engineering
Franjevačka 2	Franjevačka 2
75000 Tuzla	75000 Tuzla
Bosna i Hercegovina	Bosnia and Herzegovina

Uredništvo primilo rukopis:
2008-07-18

Manuscript received on:
2008-07-18

Prihvaćeno:
2008-09-16

Accepted on:
2008-09-16

ODREĐIVANJE MEĐUSOBNOG OTPORA UZEMLJENJA BLISKIH UZEMLJIVAČA

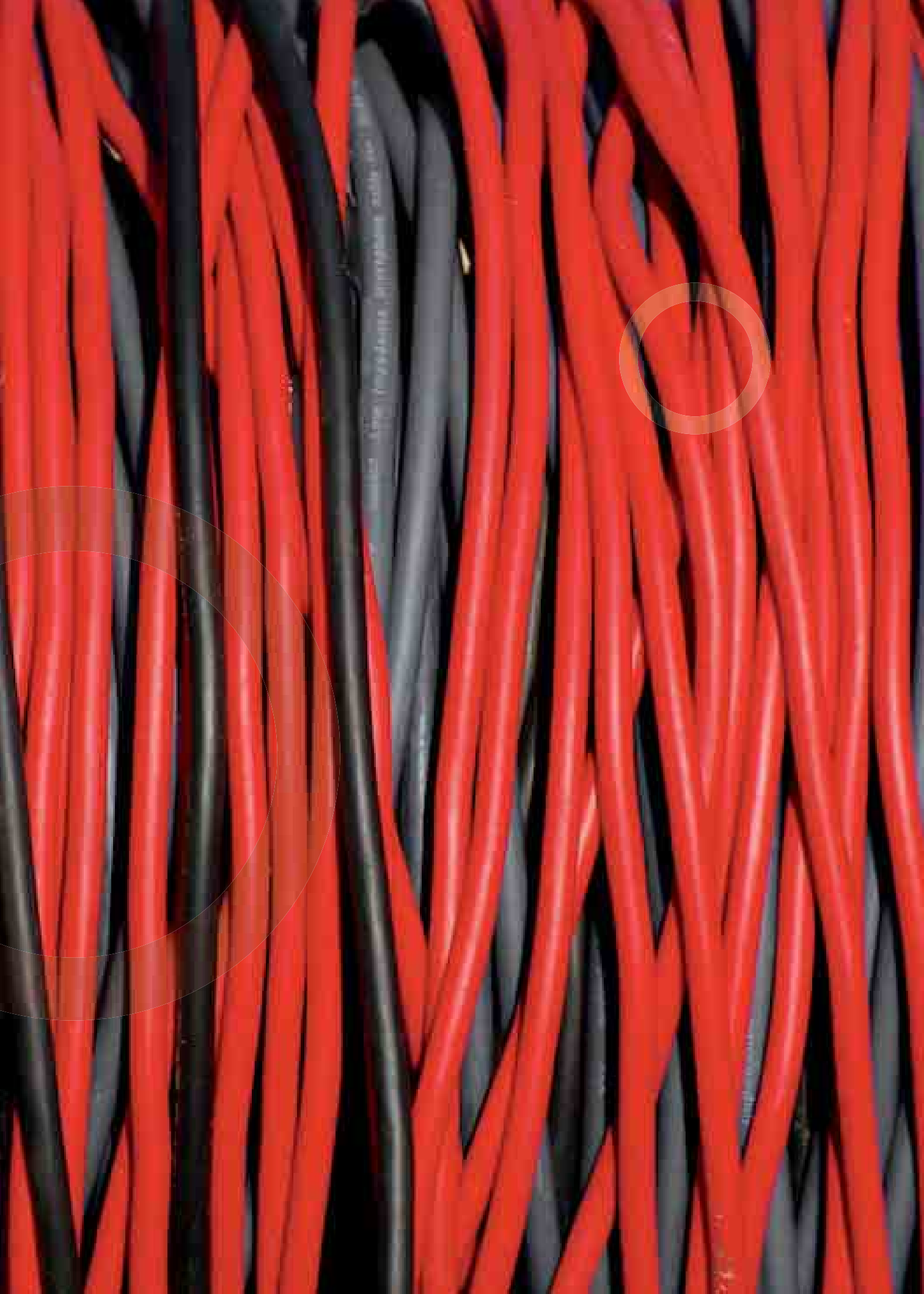
DETERMINATION OF THE MUTUAL GROUND RESISTANCE OF ADJACENT GROUNDING GRIDS

Ivan Sarajčev - Petar Sarajčev - Slavko Vujević, Split, Hrvatska

U članku je obrađena problematika određivanja međusobnog otpora uzemljenja dvaju bliskih, metalno povezanih, uzemljivača. S tom svrhom izveden je izvorni analitički izraz za izračunavanje odgovarajućeg međusobnog otpora uzemljenja među bliskim uzemljivačima. Naime, kod bliskih uzemljivača nazočna je složena elektromagnetska sprega među njima. Pritom je posebice snažno izražena vodljiva komponenta ove sprege. Ona u stanju dozernog kratkog spoja utječe na povećanje ukupnog otpora uzemljenja pripadnog uzemljivačkog sustava. Poznavanje spomenutog međusobnog otpora uzemljenja je inače bitno za korektno određivanje raspodjele parcijalnih struja dozernog kratkog spoja u sustavu bliskih uzemljivača. Razmatrana problematika određivanja međusobnog otpora uzemljenja prikazana je na primjeru dvaju konkretnih mrežastih uzemljivača ukopanih u loše vodljivo tlo.

The article discusses the determination of the mutual ground resistance of two adjacent metalically connected grounding grids. For this purpose, an original analytical expression for calculating the corresponding mutual ground resistance of two adjacent grounding grids has been developed. There is a complex electromagnetic coupling between adjacent grounding grids. The conductive component of this coupling is particularly evident. During a ground fault, this component markedly increases the ground resistance of the corresponding grounding system. It is essential to establish the aforementioned mutual ground resistance correctly in order to determine the distribution of the partial ground fault currents in a system of adjacent grounding grids. The determination of mutual ground resistance is presented using two specific grounding grids buried in poorly conductive soil.

Ključne riječi: bliski uzemljivač; međusobni otpor uzemljenja; vodljiva sprega
Key words: adjacent grounding grid; mutual ground resistance; conductive coupling



1 UVOD

Uzemljivači su redovito sastavni dijelovi elektroenergetskih postrojenja, koja se susreću u elektroprivredi ili u industriji. Oni se sastoje od niza galvanski spojenih vodiča (uzemljivačko uže, traka), ukopanih u zemlji. Na uzemljivače se redovito spajaju i zaštitna užad nadzemnih vodova, kao i metalni ekrani elektroenergetskih kabela. Tako nastaju složeni sustavi uzemljenja [1].

Osnovne značajke uzemljivača, odnosno uzemljivačkog sustava, bitne za njegovu zaštitno djelovanje jesu:

otpor uzemljenja uzemljivača, odnosno ukupni otpor uzemljenja uzemljivačkog sustava, potencijal uzemljivača, odnosno uzemljivačkog sustava, u odnosu na tzv. neutralnu zemlju, raspodjela potencijala po površini tla nad uzemljivačem kao i u njegovoj okolini (potencijalno polje), naponi dodira i koraka koje ljudi mogu premostiti tijekom trajanja kvara sa zemljom; isti su dijelovi potencijalnog lijevka uzemljivača.

Glede zaštitnog djelovanja uzemljivača, odnosno uzemljivačkog sustava, najnepovoljniji kvarovi sa zemljom jesu: jednopolni kratki spoj u uzemljenoj mreži (mreže s izravno ili posredno uzemljenim zvjezdastima energetske transformatora) i dvostruki zemljospoj u izoliranoj mreži.

Kod bliskih, metalno spojenih, uzemljivača u stanju dozemnog kvara dolazi do snažne konduktivne sprege među njima, [2]. Naime, svaki od pripadnih uzemljivača nalazi se ujedno u potencijalnom polju susjednog uzemljivača. Stoga se otežava (smanjuje) odvođenje struje dozemnog kvara s dotičnih uzemljivača u zemlju. To ima za posljedicu povećanje ukupnog otpora uzemljenja pripadnog uzemljivačkog sustava u odnosu na paralelni spoj uzemljivača bez utjecaja vodljive veze među njima.

Dakle, u ovom slučaju povećanje ukupnog otpora uzemljenja može se uvažiti uvođenjem međusobnog otpora uzemljenja. Pomoću međusobnog otpora uzemljenja uvažava se međudjelovanje uzemljivača kada oni odvedu struju u okolno tlo. Dakle, pri modeliranju bliskih uzemljivača koristi se međusobni otpor uzemljenja. Pod pojmom bliski uzemljivači smatraju se oni uzemljivači kod kojih je međusobna udaljenost mjerljiva s najstaknutijom dimenzijom uzemljivača. Određivanje međusobnog otpora uzemljenja i njegov utjecaj na ukupni otpor uzemljenja prikazuje se u ovom radu.

1 INTRODUCTION

Grounding grids are essential components of electrical power switchyards, which are encountered in electrical power supply and industry. They consist of a series of galvanically connected conductors (ground wires, grounding strips) buried in the soil. Overhead shield wires are regularly connected to grounding grids, as well as the metallic screens of electric power cables, thereby creating complex grounding systems [1].

The basic properties of a grounding grid, i.e. grounding system, essential for the protective function are as follows:

the ground resistance of a grounding grid, i.e. the total ground resistance of a grounding system, the potential of a grounding grid, i.e. a grounding system, in reference to the neutral ground, the distribution of potential on the ground surface over the grounding grid as well as in its vicinity (potential field), touch voltage and step voltage, which a person could bridge during a ground fault; they present parts of the potential profile of the grounding grid.

Regarding the protective function of a grounding grid, i.e. a grounding system, the worst case ground faults are as follows: a single pole short circuit in grounded networks (networks where the neutral points of the power transformers are directly or indirectly grounded) and a double ground fault in networks with isolated neutral points.

With metallically connected adjacent grounding grids during a ground fault, there is strong conductive coupling between them [2]. Each of the corresponding grounding grids is also located in the potential field of the neighboring grounding grid. The dissipation of the ground fault current from the grounding grid to the ground is thereby impeded. Consequently, the total ground resistance of the corresponding grounding system is increased.

According to the network theory, in this case the increase of the total ground resistance can be taken into account by introducing mutual ground resistance. Using mutual ground resistance, it is possible to take the interactions of the grounding grids into account when they conduct the current into the surrounding soil. In modeling adjacent grounding grids, mutual ground resistance is used. Adjacent grounding grids refer to grounding grids at a mutual distance that is approximately equal to one or two times their largest dimension. This article presents the determination of mutual ground resistance and its impact on total ground resistance.

2 KOEFICIJENT PORASTA UKUPNOG OTPORA UZEMLJENJA

Na slici 1 prikazan je sustav bliskih uzemljivača A i B. Oni pripadaju odgovarajućim postrojenjima A i B. Dotični uzemljivači su međusobno dobro metalno spojeni. Primjerice, oni su povezani, osim s uzemljivačkim užetom, još i s metalnim ekranima elektroenergetskih kabela koji povezuju pripadna postrojenja A i B. Na današnjem stupnju tehničkog razvika, to su najčešće jednožilni kabele s krutom izolacijom izvedenom od umreženog polietilena [3]. Njihov metalni ekran je dobro vodljiv (izrađen je od bakra), a preko njega se nalazi vanjski plašt od izolacijskog materijala (PVC, polietilen, poliolefin i sl.). Dotični vanjski plašt svrstava ove kabele u skupinu tzv. kabela izoliranih u odnosu na zemlju [4] i [5]. Naime, kod ovih kabela ne dolazi do odvođenja dijela struje dozemnog kvara s metalnog ekrana kabela u okolno tlo.

Oznake upotrijebljene na slici 1 imaju sljedeća značenja:

- R_A, R_B - vlastiti otpori uzemljenja uzemljivača A i B, respektivno,
- R_M - međusobni otpor uzemljenja zbog vodljive sprege između uzemljivača A i B,
- I_u - ukupna struja koju odvodi pripadni uzemljivački sustav,
- I_A, I_B - parcijalne struje koje odvođe uzemljivači A i B, respektivno,
- V_A, V_B - potencijali, respektivno, uzemljivača A i B u odnosu na neutralnu zemlju.

S obzirom da su dotični uzemljivači dobro galvaniski spojeni, zadovoljena je sljedeća relacija:

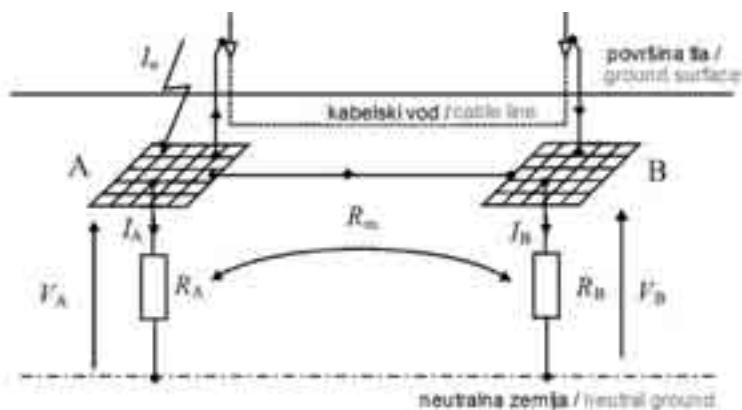
2 THE COEFFICIENT OF INCREASE OF TOTAL GROUND RESISTANCE

In Figure 1, a system of adjacent Grounding Grids A and B, is presented. They belong to the corresponding substations, A and B. These grounding grids are metallically connected. Besides being connected by the ground wire, they are also connected by metallic power cable screens which connect the corresponding substations, A and B. At the present level of technical development, these are most commonly single core cables with solid polyethylene (XLPE) insulation [3]. Their metal screen is a good conductor (copper), with an outer jacket of insulating material (PVC, polyethylene, polyolefin etc.). Due to the outer jacket, this cable is classified in the group of so-called insulated cables in reference to the ground [4] and [5]. With these cables, the ground fault current does not dissipate from the metallic cable screen into the surrounding soil.

The symbols used in Figure 1 have the following definitions:

- R_A, R_B - ground resistance of Grounding Grids A and B, respectively
- R_M - mutual ground resistance due to conductive coupling between grounding grids, A and B,
- I_u - total current passing through the corresponding grounding system,
- I_A, I_B - partial currents passing through Grounding Grids A and B, respectively,
- V_A, V_B - potentials, of Grounding Grids A and B, respectively, in reference to the neutral ground.

Since said grounding grids are firmly connected galvanically, the following expression is valid:



Slika 1 – Nadomjesna shema sustava bliskih uzemljivača A i B
Figure 1 – Equivalent diagram of a system of adjacent grounding grids, A and B

$$V_A \approx V_B \approx V_u \quad (1)$$

Temeljem potonje relacije, odgovarajući ukupni otpor uzemljenja pripadnog uzemljivačkog sustava jednak je sljedećem izrazu:

Based upon the previous expression, the corresponding total ground resistance of the grounding system is equal to the following expression:

$$R_u = \frac{V_u}{I_u} \quad (2)$$

U ovaj otpor uzemljenja uključena je, dakako, i konduktivna sprega koja vlada među spomenutim bliskim uzemljivačima. Naime, uzemljivač A nalazi se u potencijalnom lijevku uzemljivača B i obratno. To dovodi do povećanja ukupnog otpora uzemljenja navedenog sustava bliskih uzemljivača. Može se stoga postaviti sljedeći omjer:

This ground resistance also includes the conductive coupling that features prominently between the aforementioned adjacent grounding grids. Grounding Grid A is located in the potential profile of Grounding Grid B, and vice versa. This leads to an increase in the total ground resistance of the system of adjacent grounding grids. Therefore, the following ratio can be established:

$$\eta = \frac{R_u}{R'_u} \quad (3)$$

u kojem su:

in which:

η - koeficijent porasta ukupnog otpora uzemljenja; on općenito zadovoljava relaciju $\eta \geq 1$,
 R'_u - nadomjesni otpor uzemljenja spomenutih uzemljivača, bez utjecaja vodljive sprege među njima, njegova je vrijednost dana sljedećim izrazom:

η - coefficient of increase of total ground resistance, which generally satisfies the expression $\eta \geq 1$,
 R'_u - equivalent ground resistance of the aforementioned grounding grids, without the effect of the conductive coupling between them, the value of which is expressed as follows:

$$R'_u = \frac{R_A \cdot R_B}{R_A + R_B} \quad (4)$$

3 ANALITIČKI IZVOD MEĐUSOBNOG OTPORA UZEMLJENJA

3 ANALYTIC DERIVATION OF MUTUAL GROUND RESISTANCE

Korištenjem oznaka i simbolike prezentirane na slici 1 i relacije (1), stanje u navedenom uzemljivačkom sustavu može se opisati sljedećom matricnom jednadžbom:

By using the symbols presented in Figure 1 and Expression (1), the aforementioned grounding system can be described by the following matrix equation:

$$\begin{bmatrix} R_A & R_m \\ R_m & R_B \end{bmatrix} \cdot \begin{Bmatrix} I_A \\ I_B \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \cdot V_u \quad (5)$$

Rješenjem potonje matricne jednadžbe po parcijalnim strujama I_A i I_B , dobije se:

By solving the above matrix equation according to partial currents I_A and I_B , the following is obtained:

$$I_A = \frac{R_B - R_m}{R_A \cdot R_B - R_m^2} \cdot V_u, \quad (6)$$

$$I_B = \frac{R_A - R_m}{R_A \cdot R_B - R_m^2} \cdot V_u. \quad (7)$$

Nadalje, sa slike 1, također, slijedi da je:

Furthermore, from Figure 1, it also follows that:

$$I_u = I_A + I_B. \quad (8)$$

Uvrštenjem (6) i (7) u (8), dobije se:

By inserting (6) and (7) into Expression (8), the following is obtained:

$$I_u = \frac{R_A + R_B - 2 \cdot R_m}{R_A \cdot R_B - R_m^2} \cdot V_u. \quad (9)$$

Iz izraza (2) i (9), slijedi da je:

From Expressions (2) and (9), it follows that:

$$R_u = \frac{R_A \cdot R_B - R_m^2}{R_A + R_B - 2 \cdot R_m}. \quad (10)$$

Potonji izraz jasno pokazuje da međusobni otpor uzemljenja utječe na povećanje ukupnog otpora uzemljenja. Naime, za $R_m = 0$ izraz (10) poprima vrijednost prema izrazu (4).

The above expression clearly demonstrates that mutual ground resistance increases total ground resistance. For $R_m = 0$, Expression (10) obtains a value according to Expression (4).

Nakon uvrštenja izraza (4) i (10) u (3), slijedi da je:

After inserting Expressions (4) and (10) into Expression (3), it follows that:

$$\eta \cdot \frac{R_A \cdot R_B}{R_A + R_B} = \frac{R_A \cdot R_B - R_m^2}{R_A + R_B - 2 \cdot R_m}. \quad (11)$$

Rješenjem izraza (11) po veličini R_m dobiva se sljedeća kvadratna jednačba:

By solving Expression (11) according to the value R_m , the following quadratic equation is obtained:

$$R_m^2 - 2 \cdot \eta \cdot \frac{R_A \cdot R_B}{R_A + R_B} \cdot R_m + (\eta - 1) \cdot R_A \cdot R_B = 0. \quad (12)$$

Ova se kvadratna jednačba, korištenjem izraza (4), može napisati u sljedećem obliku:

By using Expression (4), this quadratic equation can be written in the following form:

$$R_m^2 - 2 \cdot \eta \cdot R'_u \cdot R_m + (\eta - 1) \cdot R'_u \cdot (R_A + R_B) = 0. \quad (13)$$

Korijeni potonje kvadratne jednačbe glase:

The roots of the above quadratic equation are as follows:

$$(R_m)_{1,2} = \eta \cdot R'_u \cdot \left(1 \pm \sqrt{1 - \frac{\eta - 1}{\eta^2} \cdot \frac{R_A + R_B}{R'_u}} \right). \quad (14)$$

Budući da fizikalno mora biti zadovoljena sljedeća relacija:

Since the following ratio must be satisfied physically:

$$R_m < \eta \cdot R'_u, \quad (15)$$

iz (14) slijedi traženo rješenje međusobnog otpora uzemljenja:

the solution sought for mutual ground resistance ensues from Expression (14):

$$R_m = \eta \cdot R'_u \cdot \left(1 - \sqrt{1 - \frac{\eta - 1}{\eta^2} \cdot \frac{R_A + R_B}{R'_u}} \right). \quad (16)$$

Ovo rješenje ima fizikalnog smisla.

This solution is physically sound.

4 PRIMJER PRORAČUNA

4 CALCULATION EXAMPLE

Za primjer proračuna su odabrani mrežasti uzemljivači A i B prema slici 2. Uzemljivač A pripada postrojenju 110 kV. Njegove su dimenzije 100 x 100 m. Uzemljivač B pripada elektrani, koju čini generator s pripadnim blok transformatorom. Dimenzije potonjeg uzemljivača jesu 25 x 25 m. Oba navedena uzemljivača su izrađena iz bakrenog užeta presjeka 70 mm². Dimenzije oka uzemljivača A neka su 10 x 10 m, a uzemljivača B 5 x 5 m, kao što je prikazano na slici 2. Neka su dotični uzemljivači ukopani u slabo vodljivo homogeno tlo specifičnog električnog otpora $\rho = 1\,000 \Omega\text{m}$, na dubini 1,2 m.

For a calculation example, Grounding Grids A and B were chosen, according to Figure 2. Grounding Grid A belongs to a 110 kV switchyard. Its dimensions are 100 x 100 m. Grounding Grid B belongs to an electrical power plant, consisting of a generator with the corresponding step-up transformer. The dimensions of the latter are 25 x 25 m. Both grounding grids are realized by copper wire, with a cross section of 70 mm². Let a mesh square of Grounding Grid A be 10 x 10 m, and 5 x 5 m for Grounding Grid B, as shown in Figure 2.

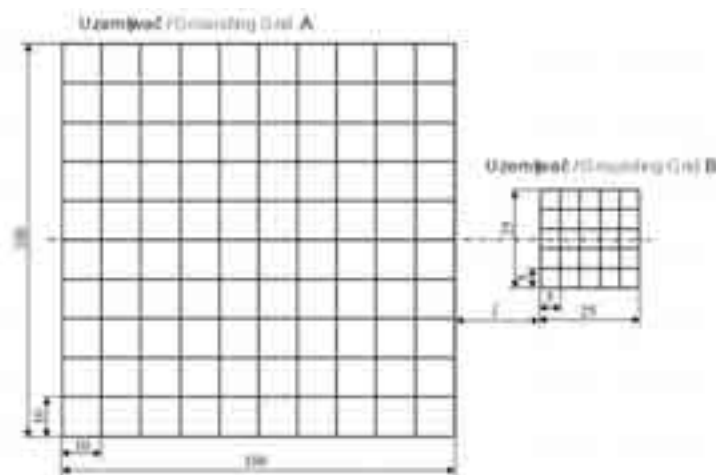
Let these grounding grids be buried in poorly conductive homogeneous soil of a specific electrical resistivity of $\rho = 1\,000 \Omega\text{m}$, at a depth of 1,2 m.

Galvanska veza među dotičnim uzemljivačima neka je ostvarena metalnim ekranima jednožilnih kabela s izolacijom od umreženog polietilena. Riječ je o tri jednožilna kabela koji čine kabelski vod 110 kV. Dotični kabelski vod povezuje spomenuti blok transformator u elektrani s navedenim postrojenjem 110 kV. Metalni ekrani dotičnih jednožilnih kabela su od bakra, presjeka 95 mm² svaki. Ovi kabeli spadaju u skupinu tzv. kabela izoliranih u odnosu na zemlju.

Let the galvanic connection between the grounding grids be achieved using a metallic single-core cable screen insulated with polyethylene (XLPE). Three single-core cables form a 110 kV cable line. This cable line connects the aforementioned step-up transformer in the power plant with the aforementioned 110 kV switchyard. The metallic screens of the single-core cables are of copper, each with a cross-section of 95 mm². These cables belong to the group of so-called insulated cables in reference to the ground.

Za potrebe numeričkih proračuna otpora rasprostiranja razmatranog složenog uzemljivačkog sustava iskorišten je računalni program EarthGrid, razvijen u sklopu izrade doktorske disertacije [6]. Računalni program EarthGrid temeljen je na frekvencijski ovisnom elektromagnetskom modelu. Dotični računalni program, pri modeliranju uzemljivačkog sustava,

For the numerical calculation of the propagation resistance of the complex grounding system under consideration, the software package EarthGrid was used. This package was developed within the framework of the preparation of a doctoral dissertation [6]. The software package EarthGrid is based upon a frequency-dependent electromagnetic model. In



Slika 2 – Dispozicija bliskih uzemljivača korištena u primjeru proračuna
Figure 2 – Disposition of adjacent grounding grids in the calculation example

koristi tehniku konačnih elemenata primijenjenu na integralnu formulaciju problema u frekvencijskoj domeni. U proračunu se uzima u obzir kompletna elektromagnetska sprega među svim segmentima vodiča koji čine uzemljivački sustav [6]. Vlastite i međusobne impedancije računaju se na osnovi metode srednjeg potencijala, koja je specijalan slučaj Galerkin-Bubnove metode. U postupku rješavanja jednadžbi potencijala koristi se tzv. tanko-žičana aproksimacija. Vodiči uzemljivačkog sustava mogu biti i izolirani u odnosu na okolno tlo, čime se uzimaju u obzir metalni ekrani jednožilnih kabela s izolacijskim vanjskim plaštem. U okviru računalnog programa EarthGriD, tlo se može promatrati kao homogeno ili pak horizontalno složeno višeslojno tlo s proizvoljnim ukupnim brojem slojeva [6].

Pomoću računalnog programa EarthGriD izračunati su prvo vlastiti otpori uzemljenja dotičnih uzemljivača bez utjecaja vodljive sprege među njima. Dobivene su, respektivno, sljedeće vrijednosti:

$$R_A = 4,474 \Omega, \quad (17)$$

$$R_B = 17,420 \Omega. \quad (18)$$

Zatim su pomoću istog računalnog programa računati ukupni otpori uzemljenja pripadnog uzemljivačkog sustava, uz uračunavanje konduktivne sprege među dotičnim uzemljivačima. To je urađeno za različite udaljenosti, l , među bliskim rubovima dotičnih uzemljivača. Naime, uzemljivač B

modeling a grounding system, this program uses the finite-element technique applied to the integral formulation of a problem in a frequency domain. The calculation takes into account the complete electromagnetic coupling among all the segments of the conductors that make up the grounding system [6]. Self-impedance and mutual impedance are calculated on the basis of the average potential method, which is a special case of the Galerkin-Bubnov method. Thin-wire approximation is used in solving the equations of potential. The conductors of a grounding system can be insulated in reference to the surrounding soil, which takes into account the metallic screens of the single-core cables with insulating outer jackets. Within the framework of the EarthGriD software package, the soil may be considered as homogenous or even horizontally stratified in multiple layers with an arbitrary total number of layers [6].

First, the self-ground resistances of the grounding grids without the influence of their mutual conductive coupling were calculated using the EarthGriD software package. The following values were obtained:

Subsequently, using the same software package, the total ground resistances of the corresponding grounding system were calculated, taking into account the mutual conductive coupling of the grounding grids. This was performed for various distances, l , between the adjacent edges of the corresponding grounding grids. Grounding Grid B was moved away

Tablica 1 – Ukupni otpori uzemljenja pripadnog uzemljivačkog sustava za različite udaljenosti među pojedinim uzemljivačima

Table 1 – The total ground resistances of the corresponding grounding system for various distances between individual grounding grids

l [m]	0,5	10	20	50	100
R_u [Ω]	4,271	4,191	4,123	3,978	3,846

odmican je od uzemljivača A, po simetriji prikazanoj na slici 2, tako da udaljenost njihovih najbližih rubova l iznosi prema tablici 1. Rezultati proračuna ukupnog otpora uzemljenja, dobiveni računalnim programom EarthGrid, prikazani su konačno u tablici 1.

from Grounding Grid A along the symmetry axis presented in Figure 2, so that the distances between their closest edges, l , are according to Table 1. The final results of the calculation of the total ground resistances, obtained using the EarthGrid software package, are presented in Table 1.

Uvrštenjem (17) i (18) u (4), dobije se:

By inserting Expressions (17) and (18) into Expression (4), the following is obtained:

$$R_u' = 3,560 \Omega. \quad (19)$$

Korištenjem vrijednosti ukupnih otpora uzemljenja danih u tablici 1 i izraza (19), slijede prema izrazu (3) odgovarajući koeficijenti porasta ukupnog otpora uzemljenja. Njihove vrijednosti su prikazane u tablici 2. Korištenjem potonjih vrijednosti (veličina η), te (17), (18) i (19), izraz (16) daje odgovarajuće vrijednosti međusobnog otpora uzemljenja. Ove su vrijednosti (veličina R_m) također prikazane u tablici 2. To je urađeno za prethodno usvojene udaljenosti, l , među bliskim uzemljivačima.

By using the values of the total ground resistances presented in Table 1 and Expression (19), the corresponding coefficients of the increase in total ground resistance ensue from Expression (3). Their values are presented in Table 2. By using these values (η), as well as Expressions (17), (18) and (19), Expression (16) yields the corresponding values of mutual ground resistance. These values (R_m) are also presented in Table 2. This was calculated for the previously adopted distance, l , between adjacent grounding grids.

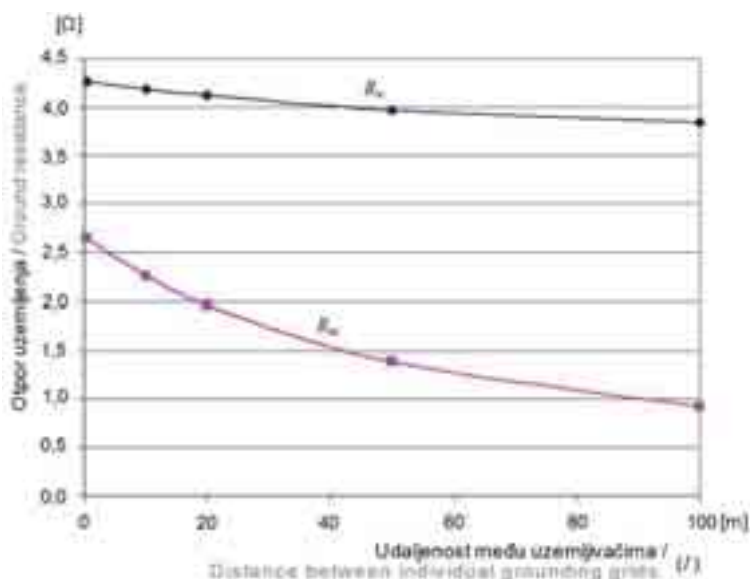
Ovisnost otpora pripadnog uzemljivačkog sustava (R_u) te ovisnost međusobnog otpora uzemljenja (R_m) o udaljenosti među uzemljivačima grafički je ilustrirana na slici 3. Korišteni su pritom, naravno, podaci iz tablica 1 i 2. Valja napomenuti da na netom spomenute veličine, osim udaljenosti, utječu i dimenzije te oblik obaju prisutnih uzemljivača. Da bi se stekao uvid u važnost spomenutih

The dependence of the ground resistance of the corresponding grounding system (R_u) and the dependence of the mutual ground resistance (R_m) on the distance between the individual grounding grids is illustrated in Figure 3, using data from Tables 1 and 2. The values mentioned, except for distance, are also affected by the dimensions and shapes of both grounding grids.

Tablica 2 – Koeficijent porasta ukupnog otpora uzemljenja i međusobni otpori uzemljenja za različite udaljenosti među pojedinim uzemljivačima

Table 2 – The coefficient of increase of the total ground resistances and mutual ground resistances at various distances between individual grounding grids

l [m]	0,5	10	20	50	100
η	1,200	1,177	1,158	1,117	1,080
R_m [Ω]	2,641	2,251	1,959	1,389	0,921



Slika 3 – Ovisnost otpora uzemljivačkog sustava i međusobnog otpora uzemljenja o udaljenosti među uzemljivačima
Figure 3 – Dependence of the ground resistance of the grounding system and the mutual ground resistance on the distance between the grounding grids.

međusobnog otpora uzemljenja između bliskih uzemljivača uveden je sljedeći omjer:

In order to obtain insight into the importance of the mutual ground resistance between adjacent grounding grids, the following ratio was introduced:

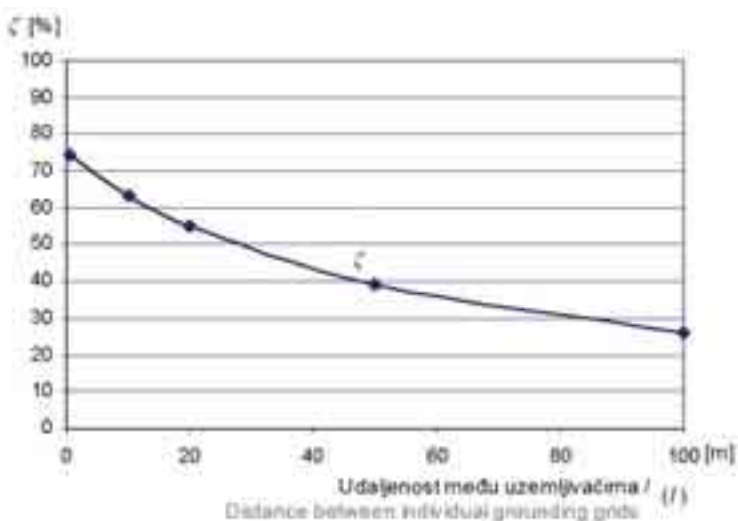
$$\zeta = \frac{R_m}{R_u} \cdot 100 (\%). \quad (20)$$

Dotični omjer (veličina ζ) je prikazan grafički na slici 4 za usvojene udaljenosti među promatranim uzemljivačima. Korištene su pritom vrijednosti međusobnog otpora uzemljenja u tablici 2 i izraza (19).

This ratio (ζ) is presented graphically in Figure 4 for the adopted distances between the grounding grids studied. Values were used for the mutual ground resistance in Table 2 and Expression (19).

Sa slike 4 je vidljivo da je važnost spomenutog

From Figure 4, it is evident that the importance of



Slika 4 – Ovisnost veličine ζ o udaljenosti među promatranim uzemljivačima
Figure 4 – Dependence of value ζ on the distance between the grounding grids studied

međusobnog otpora velik kod bliskih uzemljivača.

5 ZAKLJUČAK

U ovom je članku obrađena problematika određivanja međusobnog otpora uzemljenja bliskih uzemljivača. Naime, kod bliskih uzemljivača javlja se značajna konduktivna sprega među njima, što vodi porastu ukupnog otpora uzemljenja pripadnog uzemljivačkog sustava.

Među inim, u prezentiranom članku je izveden izvorni analitički izraz za određivanje spomenutog međusobnog otpora uzemljenja. On omogućuje lako izračunavanje pripadnog međusobnog otpora uzemljenja. Poznavanje međusobnog otpora uzemljenja je inače bitno za korektno određivanje raspodjele parcijalnih struja dozemnog kratkog spoja u pripadnom sustavu uzemljenja.

Određivanje međusobnog otpora uzemljenja provedeno je na konkretnom primjeru dvaju bliskih mrežastih uzemljivača. Pri numeričkom modeliranju dotičnih mrežastih uzemljivača korišten je sofisticirani računalni program naslova EarthGrid. Pritom je po volji mijenjana udaljenost među dotičnim uzemljivačima. Porastom dotične udaljenosti, smanjuje se vrijednost međusobnog otpora uzemljenja, i obratno.

the aforementioned mutual resistance of adjacent grounding grids is considerable.

5 CONCLUSION

In this article, the problem of determining the mutual ground resistance of adjacent grounding grids is studied. Significant conductive coupling occurs between adjacent grounding grids, leading to the increased total ground resistance of the corresponding grounding system.

Among other things, the article presents the derivation of an original analytical expression for the determination of said mutual ground resistance, which facilitates its calculation. Knowing the mutual ground resistance is necessary for the correct determination of the distribution of partial ground fault currents in the corresponding grounding system.

The determination of the mutual ground resistance was performed using a specific example of two adjacent grounding grids. In the numerical modeling of these grounding grids, a sophisticated software package, EarthGrid, was used. The distance between the aforementioned grounding grids was varied arbitrarily. As the distance increased, the value of the mutual ground resistance decreased, and vice versa.

LITERATURA / REFERENCES

- [1] MAJDANDŽIĆ, F., Uzemljivači i sustavi uzemljenja, Graphis, Zagreb, 2004.
- [2] VUJEVIĆ, S., Kombinirani postupak proračuna uzemljivača u krševitom tlu, Doktorska disertacija, Sveučilište u Splitu, FESB, Split, 1994.
- [3] ABB XLPE Cable Systems, User's Guide, Rev. 2, <http://www.abb.com/cables>
- [4] NAHMAN, J., MIJAILOVIĆ, V., Odabrana poglavlja iz visokonaponskih postrojenja, Akademski misao, Beograd, 2002.
- [5] NAHMAN, J., Uzemljenje neutralne tačke distributivnih mreža, Naučna knjiga, Beograd, 1980.
- [6] SARAJČEV, P., Elektromagnetski model sustava vodiča u višeslojnom sredstvu, Doktorska disertacija, Sveučilište u Splitu, FESB, Split, 2008.

Adresa autora:**Address of author:**

Prof. dr. sc. **Ivan Sarajčev**
Dr. sc. **Petar Sarajčev**, viši asistent
petar.sarajcev@fesb.hr
Prof. dr. sc. **Slavko Vujević**
Sveučilište u Splitu
Fakultet elektrotehnike, strojarstva i brodo-
gradnje
Ruđera Boškovića bb
21000 Split
Hrvatska

Prof. **Ivan Sarajčev**, PhD
Petar Sarajčev, PhD, Senior Assistant
petar.sarajcev@fesb.hr
Prof. **Slavko Vujević**, PhD
University of Split
Faculty of Electrical Engineering, Mechanical En-
gineering and Naval Architecture
Ruđera Boškovića bb
21000 Split
Croatia

Uredništvo primilo rukopis:
2008-07-13

Manuscript received on:
2008-07-13

Prihvaćeno:
2008-09-03

Accepted on:
2008-09-03

DINAMIČKA SVOJSTVA TIRISTORA DYNAMIC PROPERTIES OF THYRISTORS

Branislav Kuzmanović - Zoran Baus, Zagreb, Hrvatska

U radu su razmatrana dinamička svojstva tiristora. Ukratko je razmatrano svojstvo p-n barijere i objašnjen princip uključanja tiristora pomoću dvotranzistorskog modela uz zornu grafičku interpretaciju osnovne jednačbe. Zatim su razmatrana dinamička svojstva tiristora s detaljnijim osvrtom na efekte du/dt i di/dt , i na dinamički proces uključanja.

In this work the dynamic properties of thyristors are considered. The property of the p-n barrier is briefly reviewed and the principle of thyristor turn-on by means of a two-transistor model explained, along with an illustrative graphic interpretation of the basic equation. Described next are the dynamic properties of thyristors with a more detailed analysis of the du/dt and di/dt effects and the dynamic turn-on process.

Ključne riječi: dinamička svojstva tiristora; režimi rada tiristora; tiristor
Key words: dynamic properties of thyristors; thyristor; thyristor operating modes



1 UVOD

Pri izboru elemenata nekog strujnog kruga mora se voditi računa o režimu rada svakog elementa. To znači da za svaki element treba utvrditi dopuštene vrijednosti struje, napona i snage te radnu temperaturu. Prekoračenje bilo koje dopuštene vrijednosti obično dovodi do oštećenja elemenata. Posebno treba obratiti pozornost na temperaturu koja, pored ostalog, utječe na radne karakteristike elemenata. Isto tako važno je znati frekvencijsko područje rada kao i dinamička svojstva elemenata. Pri višim frekvencijama mogu doći do izražaja paraziti kapaciteti i induktiviteti, na što valja također paziti.

U strujnom krugu tiristor ima ulogu sklopke zbog čega se javljaju prijelazni procesi. Trajanje prijelaznog procesa uključanja i isključenja tiristora ne ovisi samo o dinamičkim svojstvima tiristora već i o ostalim parametrima kruga. U posljednje vrijeme razvijaju se tiristori za veće snage i više frekvencije, a za primjenu su vrlo važna njihova dinamička svojstva, brzina porasta napona (du/dt) i struje (di/dt).

Prekoračenje kritične vrijednosti du/dt dovodi do prijevremenog uključanja, a prekoračenje di/dt do uništenja tiristora. Budući da tiristor provede struju najprije u uskom kanalu, koji se proširuje određenom brzinom, nastaje njegovo lokalno pregrijavanje. To se sprječava ograničenjem brzine porasta struje. Također pri prijelaznim procesima mogu se javiti nedozvoljena strujna i naponska nadvišenja.

Glavno pitanje razvoja tiristora snage većih frekvencija povezano je s brzinom porasta struje i napona te skraćenjem vremena oslobađanja. Povećanje brzine rada tiristora nemoguće je bez poznavanja prirode prijelaznih procesa u tiristoru.

2 KARAKTERISTIČNE POJAVE I EFEKTI DINAMIČKOG REŽIMA RADA

2.1 Dinamička svojstva uključanja

Velik broj radova, pretežno eksperimentalnih, posvećeno je analizi prijelaznog procesa uključanja tiristora. Stroga analiza prijelaznih procesa u tiristoru nije provedena, a osnovni odnosi provedeni su uz cijeli niz ograničenja. Za analizu prelaznih procesa vrlo često se koristi dvotranzistorski model tiristora. Ovdje će biti razmatrana osnovna svojstva prijelaznog procesa uključanja ti-

1 INTRODUCTION

In selecting the elements of a circuit, the operating mode of each element must be taken into account. This means that permissible current, voltage and power values, as well as operating temperature, should be determined for each element. Excess of any prescribed value will as a rule cause damage to the elements. Special attention should be paid to temperature which, among other things, influences the operating characteristics of the elements. It is also important to know the frequency range and the dynamic properties of the elements. At higher temperatures, stray capacitance and inductance may appear, which should also be taken care of.

In a circuit the thyristor acts as a switch, which results in transient processes. The duration of thyristor on-and-off transient processes does not depend only on the dynamic features of the thyristor, but also on other circuit parameters. Recently, thyristors of greater power and higher frequencies are being developed, whereas very important in application are their dynamic properties, voltage rise rate (du/dt) and current rise rate (di/dt).

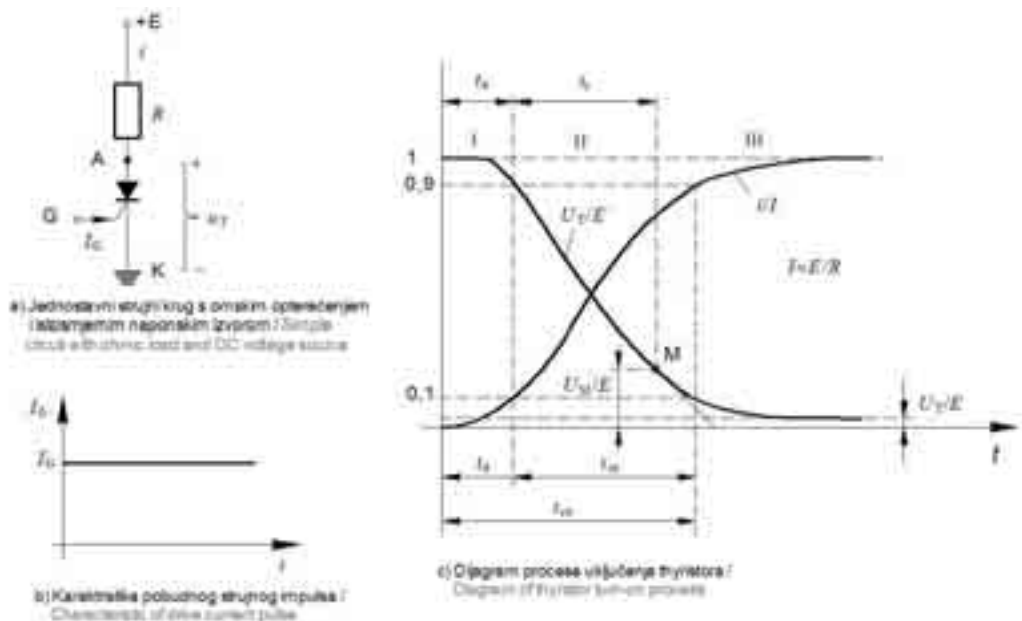
Excess of critical du/dt value will lead to a premature turn-on, excess of di/dt value will lead to the destruction of the thyristor. As the thyristor conducts electricity first in a narrow channel, which expands at a certain rate, it overheats locally. This is prevented by limiting the current rise rate. In transient processes impermissible current and voltage overshoots may also occur.

The main question encountered in developing power thyristors of higher frequencies is linked to the current and voltage rise rate and the disconnection time reduction. Increasing the thyristor's operating speed is impossible without knowing the nature of the transient processes going on in it.

2 CHARACTERISTIC PHENOMENA AND EFFECTS OF THE DYNAMIC OPERATING MODE

2.1 Dynamic turn-on features

Many works, mostly experimental ones, deal with the thyristor's transient turn-on processes. A meticulous analysis of the transient processes in the thyristor has never been made though, whereas the basic relations have been analyzed in the light of a series of restrictions. The two-transistor model of a thyristor is very often used in analyzing the transient processes. We shall discuss here the basic features of the thyristor's transient turn-on



Slika 1 – Analiza prijelaznog procesa u tiristoru
 Figure 1 – Analysis of the transient processes in the thyristor

ristora, na način pogodan za inženjersku primjenu.

Prijelazni procesi obično se razmatraju u jednostavnom strujnom krugu s omskim opterećenjem i istosmjernim naponskim izvorom (slika 1a).

Dovođenjem odgovarajućeg pobudnog strujnog impulsa $I_G > 0$ (slika 1a, 1b), tiristor će nakon nekog vremena (vrijeme uključivanja) prijeći u vodljivo stanje. U toku procesa uključivanja struja i napon tiristora mijenjaju se kontinuirano (slika 1c). Radi pojednostavljene analize, proces uključivanja može se rastaviti na više karakterističnih perioda. Međutim, navedeni autori nisu u tome jedinstveni; jedni taj proces dijele u dva perioda [1], [3], [4], [5], [6], [10], [11], [24], [30], [31], a drugi u tri [25], [27] i [53]. Pri tome se jedni služe krivuljom smanjenja napona [1], [5], [6], [10], [11], [30] i [31], a drugi krivuljom porasta struje, dok veza između te dvije krivulje nije nigdje dana. U slučaju čisto omskog opterećenja tiristorskog kruga, sasvim je svejedno koja se krivulja koristi, dok je u slučaju induktivnog opterećenja vrijeme porasta struje duže od vremena smanjenja napona. Neki autori [37], [42] i [52] dijele proces uključivanja na dvije statičke i dvije dinamičke faze. Prva dinamička faza započinje pojavom vodljivog kanala, a druga se završava rasprostriranjem struje po cijelom presjeku tiristora.

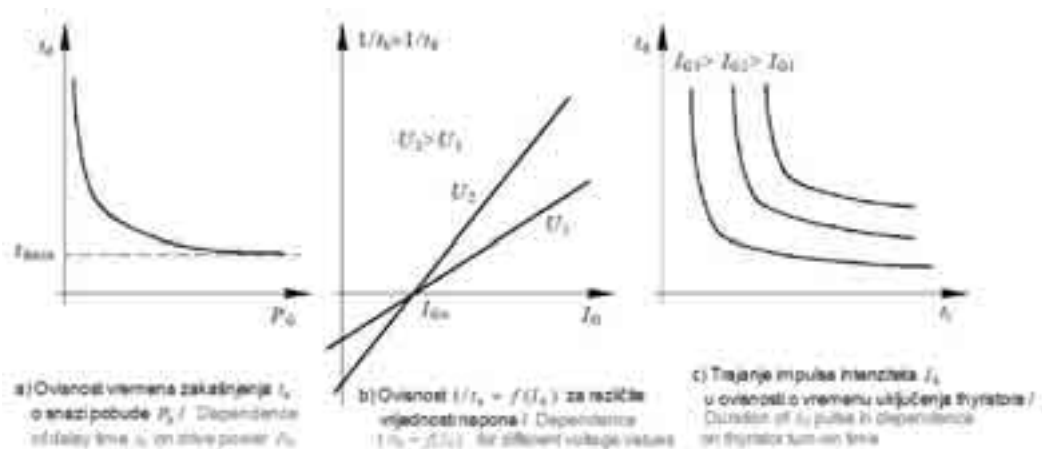
Za našu analizu prijelaznog procesa čini se najprihvatljivija naponska krivulja podijeljena u

process in a way suitable for engineering application.

Transient processes are usually studied in a simple circuit with ohmic load and dc voltage source (Figure 1a).

By bringing a certain drive pulse $I_G > 0$ (Figures 1 a, 1 b), the thyristor will after a while (turn-on time) switch over to the conductive state. During the turn-on process the thyristor's current and voltage will be changing continuously (Figure 1c). In order to simplify the analysis, the turn-on process can be broken down into several characteristic periods. However, the listed authors are not of one mind about it; some divide the process into two periods [1], [3], [4], [5], [6], [10], [11], [24], [30], [31], the others into three [25], [27], [53]. Some use the voltage decrement curve, the others use the current rise curve [1], [5], [6], [10], [11], [30], [31], but the link between these two curves is nowhere given. In the case of a purely ohmic load on the thyristor circuit it makes no difference which curve is used, while in the case of an inductive load the time of current rise time is longer than that of voltage drop. Some authors [37], [42], [52] divide the turn-on process into two static and two dynamic phases. The first dynamic phase starts with the appearance of the conductive channel, the second phase ends after the current has spread across the whole thyristor.

For our analysis of the transient process the most convenient seems to be the voltage curve divided into three characteristic periods: the delay period,



Slika 2 – Period zakašnjenja prijelaznog procesa tiristora
Figure 2 – Delay period of thyristor transient process

tri karakteristična perioda: period zakašnjenja, regeneracije i uspostavljanja stacionarnog stanja (slika 1c). Ta podjela se skoro u potpunosti podudara s podjelom prema preporuci IEC.

the regeneration period and the period of establishing stationary state (Figure 1c). Such a division is almost wholly in line with the corresponding IEC recommendation.

2.2 Period zakašnjenja

Period zakašnjenja počinje u trenutku dovođenja pobudnog impulsa I_G , pa do početka lavinskog porasta struje, što praktički odgovara sniženju anodnog napona na 90 % početne vrijednosti (slika 1c). Odgovarajući vremenski interval zove se vrijeme zakašnjenja (t_d), a sastoji se od vlastitog vremena zakašnjenja (t_0) tranzistora T_2 i vremena skupljanja kritičnog naboja (t_k). Vrijeme t_0 je vrlo kratko, koje ne ovisi o veličini strujnog impulsa I_G , već o parametrima i efektivnoj debljini baze p_2 [28]. Po isteku vremena t_0 , započinje skupljanje prostornog naboja u bazama. Tijekom vremena t_k skupi se tzv. kritični naboj (Q_{kr}), koji izaziva lavinski proces u barijeri J_2 , [4]. Eksperimentalno je utvrđeno i teoretski objašnjeno da kritični naboj ovisi o parametrima tiristora, pobudnoj struji i anodnom naponu, a praktički ne ovisi o temperaturi i neznatno je veći u statičkom režimu rada [29].

Ovisnost $1/t_k = f(I_G)$ za različite vrijednosti napona predstavlja pravac (slika 2b), pa se može lako utvrditi eksperimentalnim putem [29]. U katalozima se obično daje zavisnost vremena zakašnjenja o jakosti pobudne struje I_G ili o snazi pobude P_G (slika 2a). Što je veća pobudna struja, odnosno snaga, manje je vrijeme zakašnjenja. Međutim, postoji minimalno vrijeme zakašnjenja ($t_{dmin} = t_0$) ispod kojega se ne može aktivirati tiristor bez obzira na intenzitet impulsa (slika 2a). Ako je trajanje impulsa intenziteta I_G kraće od neke minimalne vrijednosti, također neće doći do uključivanja tiristora (slika 2c)

2.2 Delay period

The delay period starts from the moment of feeding the drive pulse I_G , to the beginning of the avalanche current rise, which practically corresponds to a decrease in anode voltage to 90 % of the starting value (Figure 1c). The corresponding time interval is called time delay (t_d) and consists of the own time delay (t_0) of transistor T_2 and the concentration time of the critical charge (t_k). Time t_0 is very short, does not depend on the quantity of the current pulse I_G , but on the parameters and effective thickness of base p_2 [28]. Upon expiry of time t_0 , the space charge grouping in the bases starts. Over the time t_k the so-called critical charge (Q_{kr}) picks up, triggering the avalanche process in barrier J_2 , [4]. It has been experimentally determined and theoretically explained that the critical charge depends on the thyristor's parameters, drive current and anode voltage, that it practically does not depend on temperature and is slightly higher in the static operating mode [29].

Dependence $1/t_k = f(I_G)$ for various voltage values is represented by a line (Figure 2b), so it is easy to determine experimentally [29]. Usually specified in catalogues is the dependence of delay time on the drive current intensity I_G or the drive power P_G (Figure 2a). The greater the excitation current, or power, the shorter the delay time. There is, however, a minimal delay time ($t_{dmin} = t_0$) below which the thyristor cannot be activated regardless of the pulse intensity (Figure 2a). Neither will the thyristor turn on if the duration of a pulse of intensity I_G is shorter than a minimal value (Figure 2c) [23], or, regardless of the duration of an impulse, if intensity is lower than the limit value I_{G0} (Figure 2b). Delay time is proportional to

[23]. Do aktiviranja tiristora također neće doći, bez obzira na dužinu trajanja impulsa, ako je intenzitet manji od granične vrijednosti I_{G0} (slika 2b). Vrijeme zakašnjenja proporcionalno je efektivnim širinama baza, pa zbog toga opada porastom anodnog napona (slika 2b), a obrnuto proporcionalno s vremenom života, pa raste s temperaturom. Smanjenjem strmine impulsa I_G , povećava se vrijeme zakašnjenja. Ta ovisnost daje se u katalozima.

2.3 Period regeneracije

U periodu regeneracije, nastavlja se punim intenzitetom započeti proces lavinskog porasta struje. Iako velik broj radova analizira proces uključivanja tiristora, vrlo malo autora razmatra prijelaz iz statičkog u dinamičko stanje, koje se karakterizira naglim padom napona. Jedna grupa autora za analizu koristi tranzistorski model [3], [21] i [23], dok drugi razmatraju kritični naboj [29], ali ni u jednom slučaju ne daju informaciju o naponu. Prvi model, koji opisuje nagli pad blokirajućeg napona, ne daje pravu sliku [38]. U radu [37] razmatran je odnos napona i struja samo u prvoj dinamičkoj fazi uključivanja tiristora pomoću jednodimenzionalnog modela, koji daje samo određenu aproksimaciju procesa. Zbog složenosti procesa ne mogu se odjednom teoretski obuhvatiti svi efekti i pojave, već se svaki efekt posebno analizira, kao npr. etapa modulacije vodljivosti baza [27], zatim lavinska injekcija [14], brzina pomicanja granice oblasti prostornog naboja [36] i [41], pad napona na n-bazi [34], proces prepolarizacije emitterskih kapaciteta [40] itd. Rezultati tih istraživanja imaju veliku važnost, prije svega za proizvodnju tiristora.

Lavinski proces započinje kada je $\alpha_1 + \alpha_2 = 1$, a egzaktniji uvjet dobio bi se pomoću dinamičkih faktora pojačanja [3]. U radu [14] pokazano je da se tiristor brže uključuje pri većim gustocama struje i većim početnim naponima. Pri većem naponu vlada jače polje u barijeri J_2 , a osim toga, lavinska injekcija se odvija u većem prostoru, pa je i proces brži.

Period regeneracije se završava u trenutku prepolarizacije barijere J_2 , tj. pri $U_{J2}=0$. Međutim, cijela barijera J_2 nije se odjednom prepolarizirala, već najprije samo na jednom vrlo uskom dijelu prijelaza, u vidu uskog vodljivog kanala, u blizini pobudne elektrode. Vodljivi kanal je najuži u bazi n, koja je ujedno najslabije vodljiva, pa je, gotovo sav pad napona na tom dijelu vodljivog kanala. Zbog toga može odgo-varajući pad napona U_M na tiristoru biti znatno veći od 0,1E (slika 1c), što ovisi o početnoj gu-

the effective widths of the bases, which is why it decreases with an increase in anode voltage (Figure 2b), and is inversely proportional to life-time, hence it rises with temperature. A decrease in the I_G impulse rise rate will lead to an increase in delay time. This dependence is given in catalogues.

2.3 Regeneration period

In the regeneration period, the started process of avalanche current rise is continued with full intensity. While the thyristor turn-on process is analyzed in many works, very few authors are studying the transition from static to dynamic state, which is characterized by a rapid voltage drop. One group of authors is using the transistor model [3], [21], [23] in the analysis, the other group is studying the critical charge [29], but neither provides information about voltage. The former model, which describes a rapid drop of the blocking voltage, does not give the true picture [38]. In a work [37] the relation between current and voltage is studied only in the first dynamic phase of the thyristor turn-on process by means of the one-dimensional model, which can give only an approximation of the process. Due to the complexity of the process, it is impossible to theoretically comprise at one stroke all the effects and phenomena, so each effect is instead individually analyzed, for instance, the base conductivity modulation stage [27], then the avalanche injection [14], the shifting speed of the space-charge limit area [36], [41], voltage drop on n-base [34], the pole reversal process of emitter capacities [40] etc. The results of these studies are of great importance, especially for the manufacture of thyristors.

The avalanche process starts when $\alpha_1 + \alpha_2 = 1$, whereas a more exact condition would be obtained by means of dynamic amplification factors [3]. A work [14] shows that the thyristor turns on faster at higher current densities and higher starting voltages. At a higher voltage a stronger field prevails in barrier J_2 and, in addition to it, the avalanche injection develops in a larger space, which in turn makes the process faster.

The regeneration period ends at the moment of pole reversal of barrier J_2 , i.e., at $U_{J2}=0$. However, the whole barrier J_2 has not changed poles at once, but first only on a very narrow transition part, in the form of a narrow conductive channel, close to the excitation electrode. The conductive channel is the narrowest in the n-base which, at the same time, is least conductive, so that nearly the entire voltage drop rests on that part of the conductive channel. That is why the corresponding voltage drop U_M on the thyristor can be much bigger than 0.1E (Figure 1c), which

stoći struje [34]. U tom trenutku krivulje napona i struje imaju točku infleksije. Odgovarajuće vrijeme trajanja perioda regeneracije zove se vrijeme regeneracije (t_r). Ono se skraćuje smanjenjem debljine baza tiristora i povećanjem anodnog napona.

2.4 Period uspostavljanja stacionarnog stanja

Period uspostavljanja stacionarnog stanja započinje u trenutku prepolarizacije središnjeg p-n prijelaza, a završava smanjenjem napona na stacionaru vrijednosti. Smanjenje napona koje nastaje zbog modulacije vodljivosti n-baze i zbog postupnog širenja vodljivog kanala po cijeloj barijeri J_2 , vrlo je važan efekt širenja vodljivog kanala, osobito kod tiristora velikih snaga, pa će biti detaljnije razmatran. Napon se u tome periodu smanjuje eksponencijalno s vremenskom konstantom (t_{rs}) [3]. Napon U_M ovisi o tipu tiristora, a veći je što je veća struja na kraju prethodnog perioda [27]. Prema tome, što je veći napon U_M , veći su gubici. Za impulсни režim rada važno je da su U_M i vremenska konstanta (t_{rs}) što manji.

Stacionarni napon U_T sastoji se od pada napona na sva tri prijelaza i na n-bazi, koja je najslabije vodljiva. Obično je taj napon mali (do 2 V), dok u nekim slučajevima može biti znatno veći [3] i [43]. To se događa u slučaju kad se u uključenom stanju sačuva u prijelazu J_2 zona tako jakog električnog polja, da driftne brzine elektrona i šupljina dostižu brzinu zasićenja. Ta se zona stvara zbog nedovoljne injekcije emitera, pa je $\alpha_1 + \alpha_2 = 1$ [43].

2.5 Vrijeme uključanja tiristora

Prema preporuci IEC, vrijeme uključanja tiristora (t_{uk}) traje od trenutka pojave pobudne struje I_G , pa sve dok napon na tiristoru ne padne na 10 % početne vrijednosti (slika 1c). To se vrijeme dijeli na vrijeme zakašnjenja (t_d) i vrijeme smanjenja napona (t_{sn}), u kojem napon padne sa 90 % na 10 % početne vrijednosti (slika 1c). Obično je $t_{sn} = t_r$ (slika 1c).

Iznos i oblik napona, kao i vrijeme uključanja, ne ovise o parametrima tiristora, već i o parametrima kruga. Eksperimentalno je utvrđeno da je vrijeme smanjenja napona kraće što je manja propusna struja i brzina porasta struje [31]. Tako npr. pri omskom opterećenju kruga struja brže raste, a napon sporije opada (crtkane linije) u odnosu na induktivno opterećenje (puna linija) (slika 3a). Zatim u omskom krugu

depends on the starting current density [34]. In this juncture the voltage and current curves have a point of inflection. The corresponding time of the regeneration period duration is referred to as regeneration time (t_r). It can be shortened by decreasing the thyristor base thickness and increasing anode voltage.

2.4 The period of establishing the stationary state

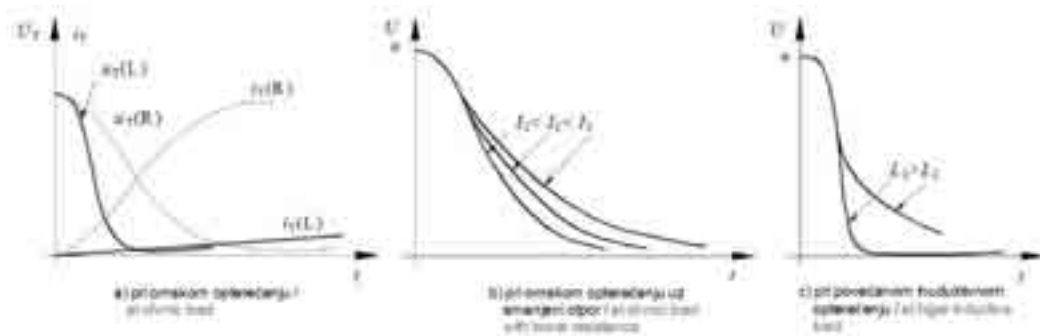
The period of establishing the stationary state starts at the pole reversal moment of the central p-n transition and ends at voltage drop to stationary values. Voltage drop resulting from the n-base conductivity modulation and due to gradual expansion of the conductive channel across the whole barrier J_2 is a very important effect of the expansion of the conductive channel, especially with big power thyristors, so it will be discussed in more detail. Voltage in that period is dropping exponentially with the time constant (t_{rs}) [3]. Voltage U_M depends on the type of thyristor, and is the bigger the bigger the current is at the end of the preceding period [27]. Therefore, the bigger the voltage U_M , the bigger the losses are. For the impulse operation mode it is important that U_M and the time constant (t_{rs}) are as small as possible.

Stationary voltage U_T consists of voltage drop at all three transitions and at the n-base which is the least conductive. That voltage is usually low (up to 2 V), whereas in some cases it may be much higher [3], [43]. This happens if in a turn-on state an area of such a strong electric field is preserved in barrier J_2 that electron drift velocities and hole reach the saturation velocity. That area is formed due to insufficient emitter injection, hence $\alpha_1 + \alpha_2 = 1$ [43].

2.5 Thyristor turn-on time

The IEC-recommended thyristor turn-on time (t_{uk}) lasts from the moment the excitation current I_G appears and until the thyristor voltage drops to 10 % of the starting value (Figure 1c). This time is divided into the delay time (t_d) and the voltage drop time (t_{sn}), within which voltage drops from 90 % to 10 % of the starting value (Figure 1c). Usually $t_{sn} = t_r$ (Figure 1c).

The voltage amount and format, just as the turn-on time, do not depend on thyristor parameters but on circuit parameters. It has been established experimentally that the voltage drop time is the shorter the smaller the forward current and the current rise rate are [31]. Thus in the case of an ohmic circuit load current rise is faster and voltage drop is slower (dotted lines) in relation to an inductive load (full line) (Figure 3a). Then in an ohmic circuit voltage drop is slower at a lower resistance (Figure 3b). An increase in circuit



Slika 3 – Ovisnost napona tiristora o parametrima strujnog kruga
Figure 3 – Dependence of thyristor voltage on current circuit parameters

napon sporije opada pri manjem otporu (slika 3b). Povećavanjem induktiviteta kruga smanjuje se brzina porasta struje, a napon brže opada (slika 3c), ali samo do određene granice.

Ako induktivitet prekorači kritičnu vrijednost, struja će presporo rasti, pa je potrebno duže vrijeme da struja postigne vrijednost struje pridržavanja. Zbog toga vrijeme uključivanja znatno poraste. Eksperimentalni rezultati, znatno se razlikuju od teoretskih; vrijeme uključivanja je kraće, a pri većim naponima neznatno ovisi o debljini baze. Pri većim naponima kraće je vrijeme uključivanja zbog jačeg lavinskog efekta, koji znatno skraćuje vrijeme regeneracije (t_r).

Značajan utjecaj na vrijeme uključivanja ima električno polje u n-bazi, koje se javlja u periodu porasta struje. Eksperimentalna istraživanja [36] i [42], pokazala su, da se pri velikoj gustoći struje u n-bazi formira jako električno polje. Pri tome je dominantna driftna komponentna struja, pa je veći pad napona na tiristoru, a vrijeme uključivanja duže.

Na kraju treba istaći da se vrijeme uključivanja produžuje porastom temperature.

2.6 Rasprostiranje uključelog stanja

2.6.1 Opći pregled

Velika praktična važnost i složenost procesa rasprostiranja uključelog stanja razlog su da je na tu temu napisan velik broj radova, a najznačajniji su [37], [40], [41], [45] do [47] i [52]. Većina navedenih radova temelji se na eksperimentalnim istraživanjima: mjerenju pada napona, mjerenju struje oporavka, mjerenju pomoću sondi, a primjenjuje se elektronsko-optička mjerna tehnika. Većina eksperimentalnih rezultata nema potpunu fizikalnu interpretaciju. Postojeće teorije rasprostiranja uključelog stanja na bazi difuzije [49] i na bazi drifta

inductance will lead to a decrease in the current rise rate, and voltage will be dropping faster (Figure 3c), but only up to a certain point.

If inductance exceeds the critical value, current will grow too slow, so more time will be needed for current to reach the holding current value. For that reason the turn-on time will be considerably longer. The experimental results greatly differ from the theoretical ones; the turn-on time is shorter, and at higher voltages slightly depends on the base thickness. At higher voltages the turn-on time is shorter due to a stronger avalanche effect which significantly shortens the regeneration time (t_r).

A considerable influence on the turn-on time is exerted by the electric field in the n-base which appears in the period of current rise. Experimental research [36], [42] has shown that at a high density of current in the n-base a strong electric field is formed. Dominant in this respect is the drift component current, with a result that voltage drop is greater on the thyristor, and the turn-on time is longer.

Finally, it should be noted that the turn-on time is extended with temperature rise.

2.6 Propagation of turn-on state

2.6.1 A general survey

The great practical importance and complexity of the turn-on state propagation explain why a lot of works have been written on the subject, the most important among them being [37], [40], [41], [45] to [47], [52]. Most of the listed works are based on experimental research: voltage drop measurement, recovery current measurement, measurement by means of probes, as well as optoelectronic measurement technique. Most experimental results lack full physical interpretation. The existing theories of turn-on state propagation, diffusion-based

[54] zasnovane su na grubim modelima iz kojih se ne može ocijeniti relativna uloga tih mehanizama u realnim tiristorima. Maphan [47] i [48], prvi je objasnio da do uništenja tiristora dolazi pri presporom rasprostiranju uključenog stanja po cijeloj barijeri J_2 . Tu pojavu povezao je s brzinom porasta struje i nazvao je efekt di/dt . On je jednostavnim mjerenjem pomoću pomoćne upravljačke priključnice utvrdio da je brzina rasprostiranja uključenog stanja 0,1 mm/ μ s. Kasniji radovi pokazuju da ta brzina nije konstantna, a najkompletnija slika o tome dana je u eksperimentalnim radovima [39] i [40].

2.6.2 Efekt di/dt

Uključenje tiristora nastaje najprije na uskom području u blizini upravljačke elektrode, formirajući u barijeru J_2 uski vodljivi kanal koji se zatim širi određenom brzinom. Početna gustoća struje u uskom kanalu mnogo puta je veća od stacionarne vrijednosti. Ta velika početna gustoća struje izaziva lokalno pregrijavanje tiristora, pa se pojavljuje tzv. vruća točka. Širenjem vodljivog kanala smanjuje se gustoća struje, čija vrijednost ovisi o brzini širenja vodljivog kanala i o brzini porasta struje di/dt . Odgovarajuća zavisnost može se matematički izraziti relacijom

$$\frac{di}{dt} = j \frac{ds}{dt} + \frac{dj}{dt} s, \quad (1)$$

gdje je:

s – trenutni presjek vodljivog kanala.

Vodljivi kanal najsporije se širi u n-bazi u blizini prijelaza J_2 [40], gdje vlada najveća gustoća struje i gotovo sav pad napona, pa na tom mjestu nastaje najveće zagrijavanje.

Smanjenje napona na tiristoru također ovisi o smanjenju gustoće struje, a lokalno zagrijavanje može se odrediti iz analize trenutne snage (slika 4). U promatranom slučaju, trenutna snaga ($p = u \cdot i > 0$, slika 4a) predstavlja brzinu generiranja topline u tiristoru. Za zornu predodžbu generirane topline u tiristoru zgodno je razmatrati odnos trenutne snage (p) i trenutnog presjeka vodljivog kanala (s):

$$\frac{p}{s} = \frac{u \cdot i}{s} = u \cdot j, \quad (2)$$

gdje je j trenutna gustoća struje.

[49] and drift-based [54], rely on rough-and-ready models with which it is not possible to assess the relative role of these mechanisms in real thyristors. Maphan [47], [48] was the first to explain that the destruction of thyristors occurs when the turn-on state propagation throughout the barrier J_2 is too slow. He linked this phenomenon to the current rise rate and called it di/dt effect. Applying a simple method of measuring by means of an auxiliary control clamp, he found that the turn-on state propagation velocity was 0,1 mm/ μ s. Latter-day works show that this velocity is not constant, whereas the fullest picture of it is given in experimental works [39], [40].

2.6.2 di/dt effect

A thyristor turns on first in the narrow area close to the control electrode forming into the barrier J_2 a narrow conductive channel which then expands at a certain rate. The starting current density in the narrow channel is many times higher than the stationary value. This high starting current density causes local overheating of the thyristor and, as a result, a hot spot appears. The expansion of the conductive channel leads a decrease in the density of the current, the value of which depends on the expansion rate of the conductive channel and the rate of current rise di/dt . Appropriate dependence can be mathematically expressed by the following relation

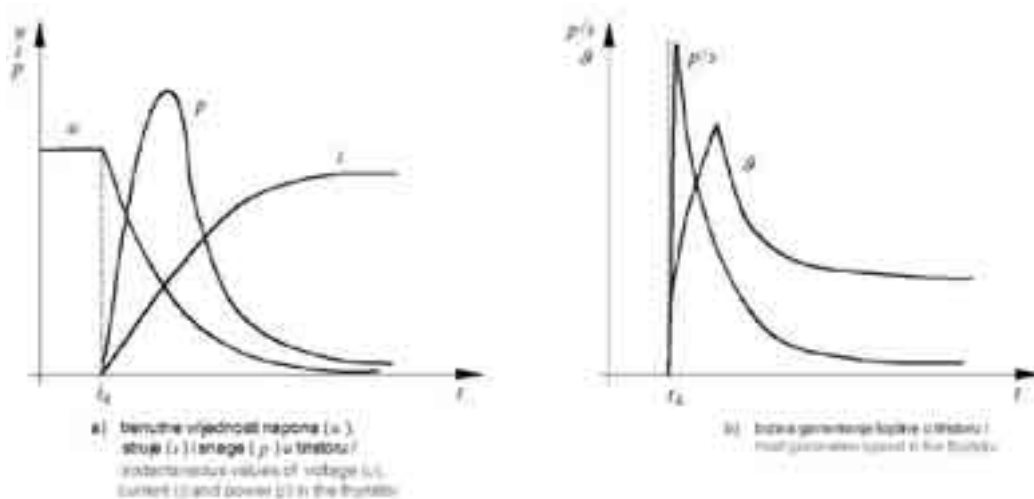
where:

s – instantaneous size of the conductive channel.

The conductive channel is expanding at the lowest rate in the n-base close to barrier J_2 [40], where the highest current density and nearly the whole voltage drop take place, which is why the strongest heating is generated here.

Voltage drop on the thyristor also depends on the decrease in current density, and local heating can be determined from an analysis of the instantaneous power (Figure 4). In the considered case the instantaneous power ($p = u \cdot i > 0$, Figure 4a) represents the rate of heat generation in the thyristor. As an illustration of heat generated in the thyristor it is convenient to study the relation between the instantaneous power (p) and the instantaneous size of the conductive channel (s):

where j is the instantaneous current density.



Slika 4 – Analiza trenutne električne snage u tiristoru
Figure 4 – Analysis of instantaneous electric power in the thyristor

Maksimalna vrijednost danog omjera (jednadžba 2) nastaje u trenutku formiranja vodljivog kanala (slika 4b). Nakon kraćeg vremena na tome mjestu stvara se maksimalna temperatura u toku jednog ciklusa (slika 4b), koja može izazvati lokalni toplinski proboj tiristora. Smanjenje lokalne tjemene temperature postiže se smanjenjem gustoće struje u prvoj fazi procesa uključivanja. S većom pobudnom strujom I_G postiže se veća početna površina uključivanja, tj. manja početna gustoća struje [52] i [54], a osim toga sporija je brzina porasta struje i kraće vrijeme uključivanja [52] i [55]. Međutim, pobudna struja ne smije prekoračiti dozvoljenu vrijednost zbog mogućeg oštećenja tiristora.

Tiristor je građen nehomogeno, pa se uvijek lokalno uključuje bez obzira na način aktiviranja. Ta lokalna točka također se zadnja isključuje u procesu isključenja tiristora [52], zbog čega je u cikličkom režimu rada, di/dt svojstvo lošije.

Poboljšanje di/dt svojstva, može se postići povećanjem početne vodljivosti i brzine rasprostiranja uključenog stanja. Oba ta faktora ovise o pobudnoj struji te o parametrima i geometrijskim odnosima p-n-p-n strukture [55].

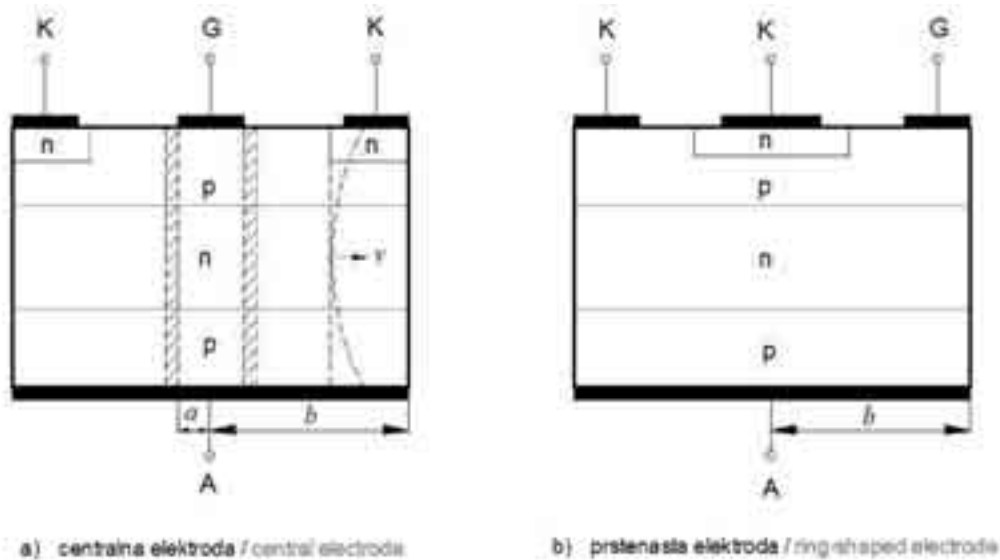
Pokušalo se raznim konstrukcijama pobudne elektrode, a ističu se konstrukcije s centralnom i prstenastom elektrodom (slike 5a i 5b). Poboljšanja su neznatna, jer tiristor i dalje najprije provode na ograničeno malom području uz rub elektrode. Tiristor s prstenastom elektrodom ima nešto veći di/dt , a s centralnom elektrodom ima kraće vrijeme uključivanja cijele površine [55], što je povoljnije za rad na višim frekvencijama.

The maximum value of a given ratio (equation 2) occurs at the moment in which the conductive channel is formed (Figure 4b). After a shorter lapse of time, at that place a maximal temperature develops in the course of a cycle (Figure 4b) which can cause a local thermal breakdown of the thyristor. Decrease in local peak temperature is achieved by lowering the current density in the first turn-on phase. With more drive current I_G a larger starting turn-on surface is attained and thereby a smaller starting current density [52], [54]; besides, the rate of current rise is slower and the turn-on time shorter [52], [55]. However, excitation current may not exceed the permissible value to avoid possible damage on the thyristor.

The thyristor's architecture is inhomogeneous, so it always turns on locally regardless of how it is activated. This local point is also the last to turn off in the thyristor turn-off process [52], which is why in the cyclic operating mode the di/dt property is deteriorated.

The di/dt properties can be improved by increasing the starting conductivity and propagation rate of turn-on state. Both of these factors depend on the excitation current and the parameters and geometrical relations of the p-n-p-n structure [55].

Attempts have been made with various designs of the excitation electrode, with central and ring-shaped electrodes being best known among them (Figures 5a and 5b). Improvements are negligible, however, because the thyristor still stays some while first in a limited small area at the edge of the electrode. The thyristor with a ring-shaped electrode has a little higher di/dt , and with a central electrode it has a shorter turn-on time of the whole surface [55], which is more suitable for operation at higher frequencies [55].



Slika 5 – Vrste konstrukcije pobudne elektrode tiristora
 Figure 5 – Structure types of thyristor excitation electrode

Znatnija poboljšanja svojstva di/dt postižu se pomoću tzv. Querfeld-Emitera [53] i [55]. Znatnija poboljšanja tiristora snage postignuta su ugradnjom pomoćnog tiristora unutar glavnoga [55]. Između glavne katode i pomoćnog tiristora formira se bočno električno polje, koje povećava brzinu širenja vodljivog kanala.

More significant improvements in di/dt properties are achieved by means of the Querfeld-Emitter [53], [55]. Marked improvements have been achieved with power thyristors by installing an auxiliary thyristor into the main thyristor [55]. Between the main cathode and the auxiliary thyristor an electric side field is formed which increases the expansion rate of the conductive channel [55].

2.6.3 Utjecaj temperature i frekvencije na di/dt svojstvo

2.6.3 The influence of temperature and frequency on di/dt property

Dobro poznavanje temperaturnih svojstava tiristora vrlo je važno za praktičnu primjenu. Već je rečeno da se na mjestu početnog uključivanja tiristora razvije maksimalna temperatura, koja u toku procesa opada (slika 4b), u ovisnosti od konstante toplinskog dovoda i gustoće struje. Ako tjemena temperatura prekorači dopuštenu vrijednost, nastaje na tom mjestu trajno oštećenje tiristora. Maksimalno dopuštena lokalna temperatura ovisi o režimu rada. Za pojedinačne impulse kreće se od 900 °C do 1 300 °C [55], dok je maksimalna temperatura elemenata 100 °C do 125 °C. Iz toga proizlazi da je dopuštena vrijednost di/dt , za pojedinačne impulse mnogo veća. U repetitivnom režimu rada, moguće je gomilanje topline u okolici vodljivog kanala, pa se tiristoru dodaju rashladna tijela, ili se smanji di/dt . Porastom radne frekvencije razvija se veća količina topline u jedinici vremena, pa se može poremetiti temperaturna ravnoteža. U tom slučaju se temperaturna ravnoteža može uspostaviti sniženjem radne temperature [53].

Thorough knowledge of the temperature properties of thyristors is very important for their practical use. As already noted, at the place of the thyristor's starting turn-on a maximal temperature develops which falls as the process continues (Figure 4b) in dependence on the thermal feed constant and the current density. If the peak temperature exceeds the permissible value, the thyristor will become permanently damaged at that place. The maximal permissible local temperature depends on the operating mode. For individual impulses it ranges from 9 000 °C to 1 300 °C [55], whereas the maximal temperature of the elements stands at 100 °C to 125 °C. It follows that the permissible value di/dt for individual impulses is much higher. In the repetitive operating mode there is a possibility of heat buildup in the vicinity of the conductive channel, so coolers are added to the thyristor or di/dt is decreased. With the increase in the operating frequency, more heat develops over the unit of time, so that temperature equilibrium can be disrupted. In that case, temperature equilibrium can be established by reducing the operating temperature. [53].

Dakle, dopuštena vrijednost di/dt ovisi o temperaturi kućišta i radnoj frekvenciji. Prekoračenje brzine porasta struje di/dt dovodi do toplinskog uništenja tiristora, pri čemu treba razlikovati dva tipa:

probaj u tzv. vrućoj točki, koji nastaje zbog prevelikog di/dt , a javlja se uvijek u blizini pobudne elektrode u vidu kratera, i to već nakon nekoliko desetaka ciklusa, probaj zbog termičkih zamora, koji nastaje kao posljedica velikih temperaturnih razlika unutar tiristorske strukture. Ta vrsta probaja nastaje nakon nekoliko stotina sati rada blizu pobudne elektrode u vidu kratera.

Međutim, do probaja može također doći zbog prekoračenja vršne vrijednosti struje, iako nije došlo do prekoračenja di/dt [53]. Ta vrsta probaja ne nastaje u blizini pobudne elektrode, već u točki u kojoj dođe do prekoračenja gustoće struje.

Iz dane analize vidi se da je granica opterećenja tiristora usko vezana sa svojstvom di/dt i radnom frekvencijom.

2.6.4 Brzina rasprostiranja i ekvivalentni otpor uključenog stanja

Proces rasprostiranja uključenog stanja istražuje se vrlo intenzivno radi velike praktične važnosti i složenosti pojave. Analitički izrazi za brzinu rasprostiranja [50], [51] i [54], izvedeni na grubim modelima na bazi difuznog, odnosno driftnog mehanizma nemaju praktično značenje za realne tiristore. Razvojem mjernih metoda, prvo s povećanim brojem sondi [50], [51], [52] i [55], a zatim primjenom elektronsko-optičke tehnike, dobiven je bolji uvid u proces rasprostiranja uključenog stanja. Utvrđeno je da se taj proces odvija nejednoliko, dolazi čak do skupljanja vodljivog kanala, obično u početku procesa [50]. Najsporije se širi vodljivi kanal u n-bazi (slika 5a), i to u oblasti maksimalne gustoće struje [55], što je u suprotnosti s teorijskim rezultatima [50], [51] i [54]. Najkompletnija mjerenja rasprostiranja uključenog stanja izvršena su u radovima [52] i [55]. Ti rezultati pokazuju da brzina rasprostiranja uključenog stanja nije monotona, već ima promjenjiv karakter, naročito u početku. Ta je promjenjivost manja pri jačoj pobudi, kao i u kasnijoj fazi. Međutim, srednja brzina rasprostiranja je oko 0,1 mm/ms, kako je još Maphan utvrdio [47] i [48]. Ako je početna gustoća struje manja od neke granične vrijednosti, neće se struja proširiti po cijeloj površini.

Therefore, the permissible value di/dt depends on the temperature of the casing and the operating frequency. Excess rate of current rise di/dt will lead to a thermal destruction of the thyristor, with two types thereof to be distinguished:

breakdown in the hot spot due to excessive di/dt , occurring always in the proximity of the excitation electrode, crater-like, after just several dozens of cycles, breakdown due to thermal fatigue as a result of major temperature differences within the thyristor's structure. This type of breakdown, also crater-like, occurs after several hundred hours of operation close to the excitation electrode.

However, a breakdown can also occur as a result of an excess in peak current value, without any di/dt excess [53]. This type of breakdown does not occur in the proximity of the excitation electrode, but in the point where current density is exceeded.

This analysis shows that the load limit of a thyristor is closely linked to the di/dt property and the operating frequency.

2.6.4 Propagation rate and equivalent resistance of turn-on state

The propagation of the turn-on state process is a subject of intensive research due to a major practical importance and complexity of that phenomenon. Analytical expressions for the rate of propagation [50], [51], [54], derived from approximate models on the basis of a diffuse, drift mechanism, have no practical importance for real thyristors. More advanced measuring methods, first using more probes [50], [51], [52], [55] then optoelectronic techniques [59], [60], [82], have provided a better insight into the propagation of the turn-on state process. It has been found that this process unfolds unevenly, that it may also be accompanied by the grouping of the conductive channel, normally at the start of the process [50]. The conductive channel in the n-base is spreading at the slowest rate (Figure 5a), unexpectedly in the area of maximum current density [55], which contradicts the theoretical results [50], [51], [54]. The most comprehensive measurements of the turn-on state propagation have been performed in works [52], [55]. Their results show that the turn-on state propagation rate is not monotonous, but variable, especially at the start. This variability is less expressed at a stronger excitation, as well as in the later phase. However, the mean propagation rate is approximately 0,1 mm/ μ s, as found by Maphan already [47], [48]. If the starting density of current is lower than some limit value, it will not spread over the whole surface.

U periodu rasprostiranja uključenog stanja nije utvrđena adekvatna veza između napona i struje tiristora. Tiristor bi se mogao za taj period nadomjestiti dinamičkim otporom R_d , pa imamo da je:

$$u = U_0 + i \cdot R_d. \quad (3)$$

Dinamički otpor R_d praktički je jednak otporu uključenog kanala. Najveći dio pada napona u vodljivom kanalu otpada na n-bazu. Radi jednostavnosti, uzima se da je uključen kanal cilindričnog oblika, a brzina jednaka brzini širenja kanala kroz n-bazu. Također se uzima da je otpor vodljivog kanala po jedinici površine jednak statičkom otporu po jedinici površine, a početna površina vođenja se zanemaruje. Iz toga slijedi da je otpor vodljivog kanala:

$$R_d = R_0 \frac{S}{\int_S ds}, \quad (4)$$

gdje je: R_0 – otpor u trenutku uključanja

Pomoću te relacije dobije se dinamički otpor tiristora s centralnom pobudom (slika 5a):

$$R_d = R_0 \frac{b^2 - a^2}{2avt + v^{-2} t^2}, \quad (5)$$

gdje je:

t – vrijeme,
 \bar{v} – srednja brzina širenja vodljivog kanala.

Za prstenastu pobudu (slika 5b) je:

$$R_d = R_0 \frac{b^2}{2bv\bar{t} - v^{-2} t^2}. \quad (6)$$

Dinamički otpor u oba slučaja opada hiperbolički s vremenom, kako je utvrđeno i eksperimentalno [31] i [32]. Eksperimentalno je također utvrđeno, da je utjecaj jakosti struje na dinamički otpor zanemariv [31], te da dinamički otpor tiristora s prstenastom pobudom, brže opada [32] (slika 6a). Ta se činjenica također očituje i u izvedenim relacijama (5) i (6), što je vidljivo iz grafičkog prikaza nazivnika tih jednažbi (slika 6b).

In the turn-on state propagation period, no adequate link has been found between the thyristor's voltage and current. For that period, the thyristor may be substituted by a dynamic resistance R_d , so we get:

The dynamic resistance R_d practically equals the resistance of a turn-on channel. The bulk of voltage drop in the conductive channel goes to the n-base. For the sake of simplicity it will be assumed that the turned on channel is cylinder-shaped and that velocity equals the velocity of channel propagation across the n-base. It will also be assumed that the conductive channel resistance per unit of surface equals the static resistance per unit of surface, whereas the starting conductance surface is ignored. What follows from this is the conductive channel resistance:

where R_0 is resistance at the turn-on moment

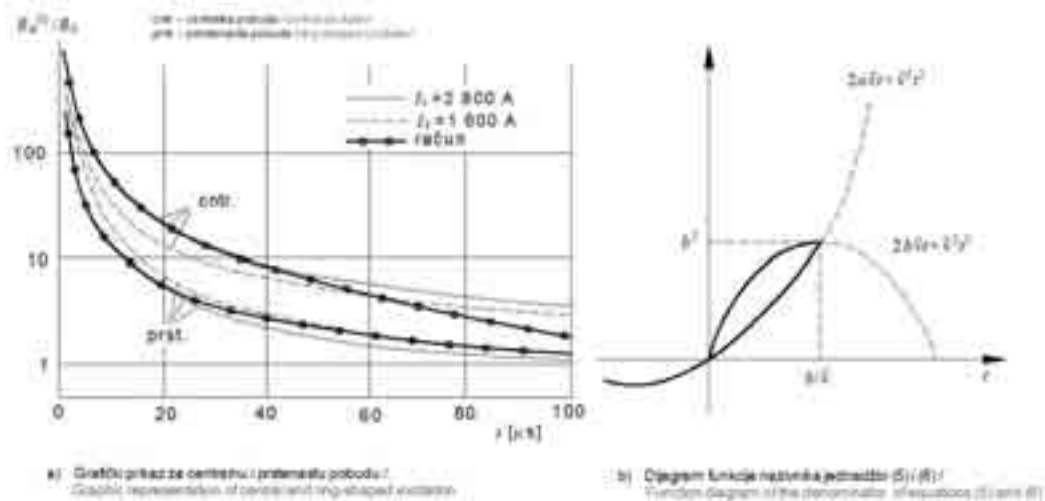
By means of this relation the dynamic resistance of the thyristor with central excitation is obtained (Figure 5a):

where:

t – time,
 \bar{v} – mean propagation speed of the conductive channel.

For the ring-shaped excitation (Figure 5b) it is:

Dynamic resistance in both cases falls hyperbolically with time, as experimentally confirmed [31], [32]. It has also been experimentally determined that the influence of current intensity on dynamic resistance is negligible [31] and that the dynamic resistance of a thyristor with ring-shaped excitation falls faster [32] (Figure 6a). This fact is also reflected on the derived relations (5), (6), as shown in the graphic representation of the denominator of these equations (Figure 6b).



Slika 6 – Ovisnost dinamičkog otpora tiristora s vremenom
 Figure 6 – Time dependence of thyristor's dynamic resistance

Eksperimentalno je utvrđeno [32] da je brzina širenja vodljivog kanala kod prstenaste pobude manja, a u početku procesa u oba je slučaja ta brzina dosta mala [32]. Na slici 6a prikazani su rezultati mjerenja dinamičkog otpora u [32] i ucrtane su odgovarajuće numeričke vrijednosti dobivene pomoću jednadžbi 5 i 6. Pri tome su uzete prosječne vrijednosti mjernih brzina u [32], i to: za centralnu pobudu $v=0,09 \text{ mm/ms}$, za prstenastu pobudnu $v=0,07 \text{ mm/}\mu\text{s}$, a potrebne dimenzije su: $a = 1,6 \text{ mm}$ i $b = 16 \text{ mm}$ [32]. Numeričke vrijednosti pokazuju zadovoljavajuću točnost, a osnovni problem je u određivanju srednje brzine. Početak procesa je osobito važan, pa treba odrediti prosječnu brzinu u tom periodu, jer o njoj ovisi točnost jednadžbe (5) i (6). Međutim, proizvođači tiristora ne daju taj podatak, kao ni dimenzije a i b . Srednja brzina, \bar{v} , mogla bi se procijeniti pomoću relacije (1). Uz poznate vrijednosti v , a i b , izrazi za dinamički otpor jednadžba (5) i (6) mogu se primijeniti pri analizi brzine porasta struje (di/dt) i pri analizi raspodjele temperature.

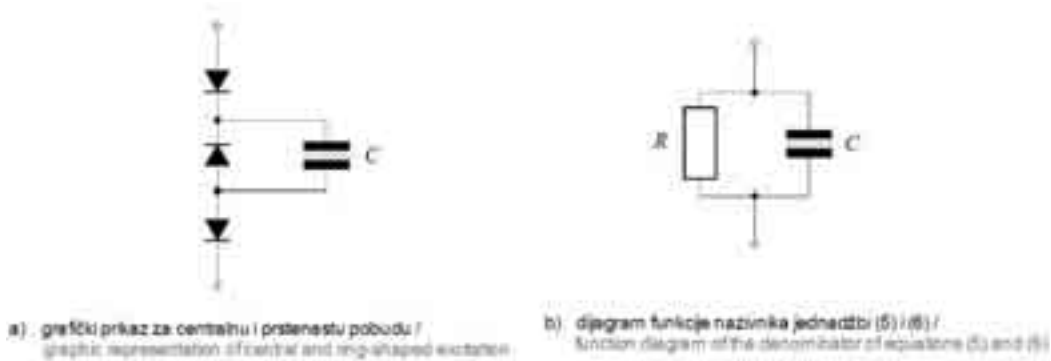
2.7 Efekt du / dt

Do uključivanja tiristora, obično neželjenog, dolazi pri prebrzom porastu anodnog napona. Ta pojava poznata je pod imenom efekt du/dt , o kojem je napisano mnogo radova, a značajniji su [1], [3], [11], [19] i [55]. U trenutku dovođenja napona, tiristor praktički djeluje kao kapacitet sastavljen od serijskog spoja kapaciteta barijera C_1 , C_2 , C_3 . Naime, otpor centralne inverzno polarizirane barijere vrlo je velik, kao i otpor vanjskih p-n prijelaza J_1 i J_3 , sve dok na njima napon ne preskoči vrijednost tzv. napo-

It has been experimentally determined [82] that the propagation rate of the conductive channel with ring-shaped excitation is smaller, that at the start of the process that rate is rather small in both cases [32]. Figure 6a shows the results of measuring dynamic resistance in [32] and appropriate numerical values obtained by means of equations (5) and (6) are entered therein. In this procedure the average values of measuring speeds in [32] are taken, viz.: for central excitation $v=0,09 \text{ mm/ms}$, for ring-shaped excitation $v=0,07 \text{ mm/}\mu\text{s}$, whereas the required dimensions are: $a = 1,6 \text{ mm}$ and $b = 16 \text{ mm}$ [32]. Numerical values show a satisfactory degree of accuracy, whereas the main problem is to determine the mean velocity. The start of the process is particularly important, so the average speed ought to be determined in that period, because the accuracy of equations (5) and (6) depends on it. However, thyristor manufacturers do not disclose this information, nor the above mentioned dimensions a and b . The mean velocity \bar{v} could be assessed by means of relation (1). Given the known values v , a and b , expressions for dynamic resistance (equations 5 and 6) can be applied in analyzing the rate of current rise (di/dt) and the distribution of temperature.

2.7 The du / dt effect

A thyristor turn-on, usually undesired, occurs when anode voltage rises too fast. This phenomenon is termed du/dt effect, which is a subject of many works, the most important among them being [1], [3], [11], [19], [55]. At the moment of voltage feed, the thyristor practically acts as a capacity composed of the series connection of the capacities of barriers C_1 , C_2 , C_3 . Namely, the resistance of the central inversely poled barrier is very strong, as is the resistance of the external p-n transitions J_1 i J_3 , as long as voltage on them does not exceed the knee voltage



Slika 7 – Ekvivalentne sheme za otpor vanjskih p-n prijelaza, za brzi porast napona
Figure 7 – Equivalent diagrams for the resistance of external p-n transitions, for a voltage jump

na koljena. Napon koljena za silicij je oko 0,5 V, nakon čega se otpor vanjskih p-n prijelaza naglo smanjuje, pa se za brzi porast napona može nadomjestiti približnom ekvivalentnom shemom (slika 7).

Detaljnija ekeivalentna shema može se dobiti pomoću prikaza tiristora s dva tranzistora [50]. Međutim, takva je shema suviše komplicirana i nepraktična za postavljeni zadatak.

U centralnom prijelazu J_2 teče kapacitivna struja.

value. The knee voltage for silicon is around 0,5 V, after which the resistance of external p-n transitions steeply drops, and for a voltage jump can thus be substituted by an approximate equivalent diagram (Figure 7).

A more detailed equivalent diagram can be obtained by means of a two-transistor thyristor diagram [50]. However, such a diagram is too complicated and impractical for the task at hand. Detaljnija ekeivalentna shema može se dobiti pomoću prikaza thyristora s dva tranzistora [50].

Capacitive current flows in the central barrier J_2

$$i_c = \frac{d}{dt}[q_2(u)] = \frac{dq_2}{du} \cdot \frac{du}{dt} = C_{J_2}(u) \frac{du}{dt}, \quad (7)$$

čiji iznos i oblik ovisi o brzini porasta napona i kapaciteta barijere J_2 .

Kada se u bazama skupi tzv. kritični naboj, započinje proces uključivanja tiristora. Naboj se brže prikuplja što je veća brzina porasta napona du/dt , dok uključivanje nastupi pri manjem naponu (slika 8a). Nadalje, kritična vrijednost du/dt opada s porastom temperature (slika 8a), a raste s početnim anodnim naponom (slika 8b).

U slučaju pozitivnog početnog napona, kapacitet barijere J_2 je manji, pa je, prema jednačbi (7), dopuštena veća vrijednost du/dt (slika 8b). Isto tako se, u slučaju negativnog početnog napona, moraju najprije sve barijere prepolarizirati, a za to je potrebno vrijeme i određena količina naboja.

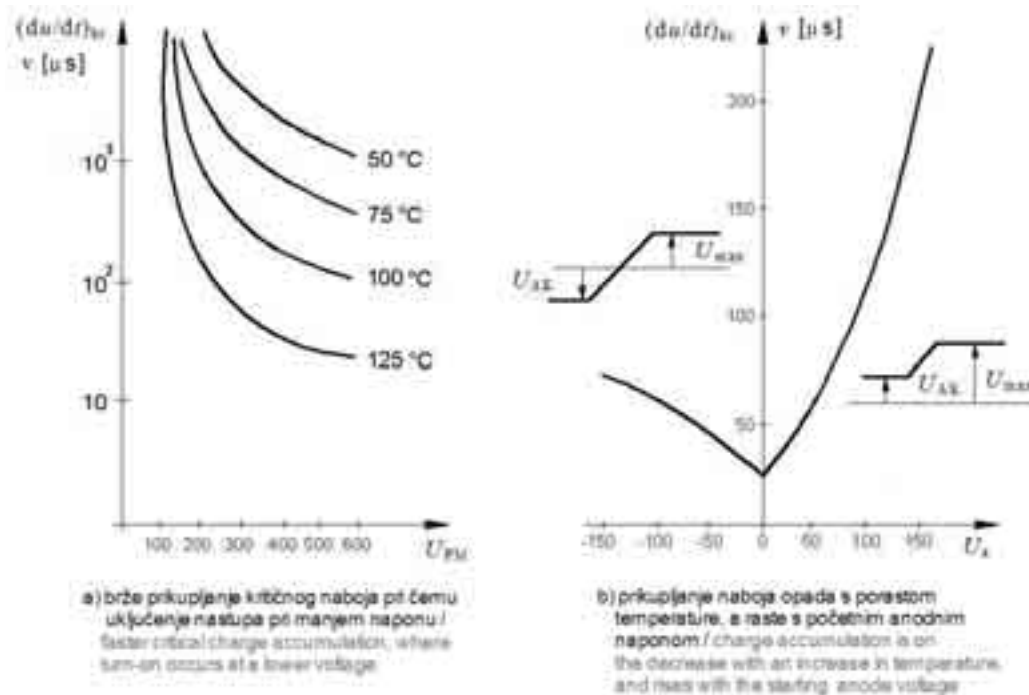
Povećanje kritične vrijednosti du/dt , može se postići povećanjem struje pridržavanja I_L i smanjenjem faktora strujnog pojačanja α_2 . Prva mogućnost je dosta ograničena, a druga se sa-

and its amount and shape depend on the rate of voltage rise and J_2 barrier capacity.

The thyristor turn-on process starts once a critical charge is reached in the bases. The charge accumulates the faster the faster is the rate of voltage rise du/dt , until the turn-on occurs at a lower voltage (Figure 8a). Furthermore, the critical value du/dt is on the decrease with an increase in temperature (Figure 8a), and rises with the starting anode voltage (Figure 8b).

In the case of a positive starting voltage, the capacity of barrier J_2 is smaller, so, according to equation (7), a higher value du/dt is allowed (Figure 8b). Likewise, in the case of a negative starting voltage all the barriers must first reverse their poles, and that requires time as well as a certain amount of charge.

The critical value of du/dt can be increased by increasing the holding current I_L and decreasing the current gain factor α_2 . The first possibility is rather limited, the second possibility is that



Slika 8 – Proces uključanja tiristora u ovisnosti o prikupljenom kritičnom naboju u bazama
Figure 8 – Thyristor turn-on process in dependence on the accumulated critical charge in the bases

stoji u tome da samo dio anodne struje prolazi kroz prijelaz J_3 . Kod manjih tiristora to se postiže stavljanjem otpora između pobudne elektrode i katode [51], a kod većih konstruktivno, pomoću tzv. kratkospojenog emitera [11]. Time je smanjena efektivna površina p-n prijelaza, a osim toga teže se aktivira tiristor strujom I_G .

Pri projektiranju tiristorskog sklopa treba obratiti posebnu pozornost na du/dt . Kod nepoželjnog preranog uključanja, može doći do uništenja tiristora, jer su u tom slučaju lošija di/dt svojstva. Kod projektiranja tiristorskih sklopova može se umjesto nelinearne sheme (slika 7a) koristiti odgovarajuća nelinearizirana nadomjesna shema (slika 7b).

U promatranom slučaju dominantni su otpor i kapacitet inverzno polarizirane barijere J_2 . Voltamperska karakteristika inverzno polarizirane barijere je, osim na samom početku, u čitavom radnom području praktički linearna, pa se može uzeti da je otpor R u nadomjesnoj shemi (slika 7b) linearan. Isto tako, kapacitet inverzno polarizirane barijere naglo se smanjuje samo kod malih napona, a u najvećem dijelu radnog područja neznatno se mijenja. Zbog toga se ekvivalentni kapacitet može također linearizirati sa srednjom vrijednošću kapaciteta barijere unutar radnog područja. Kod većine energetske dioda i tiristora, u većem dijelu radnog napona, otpor i kapacitet se neznatno mijenjaju.

only a part of anode current flows across barrier J_3 . With smaller thyristors this is attained by putting resistance between the excitation electrode and the cathode [51], with larger thyristors by way of design, with the shorted emitter [11]. This reduces the effective surface of p-n barrier and, in addition, the thyristor is harder to activate with I_G current.

In designing a thyristor unit special attention should be paid to du/dt . Apart from undesired premature turn-on, the thyristor may be destroyed, because in that case the di/dt properties are inferior. In designing a thyristor unit, an appropriate nonlinearized equivalent diagram (Figure 7b) could be used instead of a nonlinear diagram (Figure 7a).

Dominant in the considered case are the resistance and capacity of the inversely poled barrier J_2 . The volt-ampere characteristic of the inversely poled barrier is practically linear in the whole operating area, except for the very start, so it can be assumed that resistance R in the equivalent diagram (Figure 7b) is linear. Also, the capacity of the inversely poled barrier rapidly drops only at small voltages, whereas slightly varies in the most part of the operating area. For that reason the equivalent capacity can also be linearized with the mean value of the barrier capacity within the operating area. With most energy diodes and thyristors, in a greater part of the operating voltage, resistance and capacity are slightly varying.

2.8 Dinamička svojstva isključenja

2.8.1 Prijelazni proces isključenja

Tijekom procesa isključenja tiristora dolazi do odstranjivanja suvišnog naboja iz p-n-p-n strukture, koji se nagomilao u propusnom režimu rada. Tiristori se najbrže i najčešće isključuju invertiranim naponom, a isto se može postići postupnim smanjenjem struje ispod vrijednosti I_H [4], kao i negativnom pobudnom strujom, ali samo za tiristore manje snage. O tome je objavljen velik broj radova, uglavnom eksperimentalnih.

Za analizu procesa isključenja najprikladniji je tiristorski krug s čisto omskim opterećenjem (slika 1a). Invertiranjem napona započinje odstranjivanje suvišnih nosilaca, koji iz baza prelaze u vanjske slojeve; šupljine prijelaza iz baze n_1 u sloj p_1 , a elektroni iz baze p_2 u sloj n_2 . Najprije se odstranjuju sporedni nosioci uz same prelaze J_1 i J_3 , gdje se formira gradijent koncentracije manjinskih nosilaca, a prijelaz J_2 je propusno polariziran i kroz njega teku struje elektrona i šupljina. Struja šupljina je dominantna, jer je p-baza jače dopirana. Budući da je vrijeme života manjinskih nosilaca u p-bazi kraće, zatim da je ta baza uža i da sadrži manju količinu manjinskih nosilaca, koji se osim toga slabije obnavljaju preko J_2 prijelaza, najprije će iščeznuti gradijent koncentracije uz prijelaz J_3 . Pri tome započinje prepolarizacija barijere J_3 ; njen napon raste, a struja tiristora opada.

Obično je probojni napon barijere J_3 mali, pa brzo dolazi do proboja u trenutku t_2 (slika 9a). Međutim, kako na prijelazu J_1 još uvijek postoji gradijent koncentracije manjinskih nosilaca, i dalje će teći konstantna struja do trenutka t_3 kada nestaje gradijent koncentracije na prijelazu J_1 i pojavljuje se početni zaporni sloj. Barijera J_1 započinje inverznom polarizacijom, pri čemu povećava svoju debljinu i preuzima gotovo sav vanjski napon. U tom periodu (t_3 , t_5) debljina zapornog sloja povećava se toliko da otpor tiristora poraste do nekoliko stotina k Ω , što dovodi do smanjenja struje na vrijednosti struje inverzne polarizacije. U slučaju induktivnog opterećenja kruga, može doći do značajnih naponskih nadvišenja i oscilacija, kako je eksperimentalno utvrđeno [32] (slika 9b). Ta naponska nadvišenja mogu izazvati trajno oštećenje tiristora [32].

Pri induktivnom opterećenju kruga, struja u intervalu (t_0 , t_1) i (t_2 , t_3) raste, jer tiristor predstavlja zanemarivo mali otpor, dok u intervalima (t_1 , t_2) i (t_3 , t_5) struja opada zbog prepolarizacije, najprije barijere J_3 , a zatim J_1 .

2.8 Dynamic turn-off properties

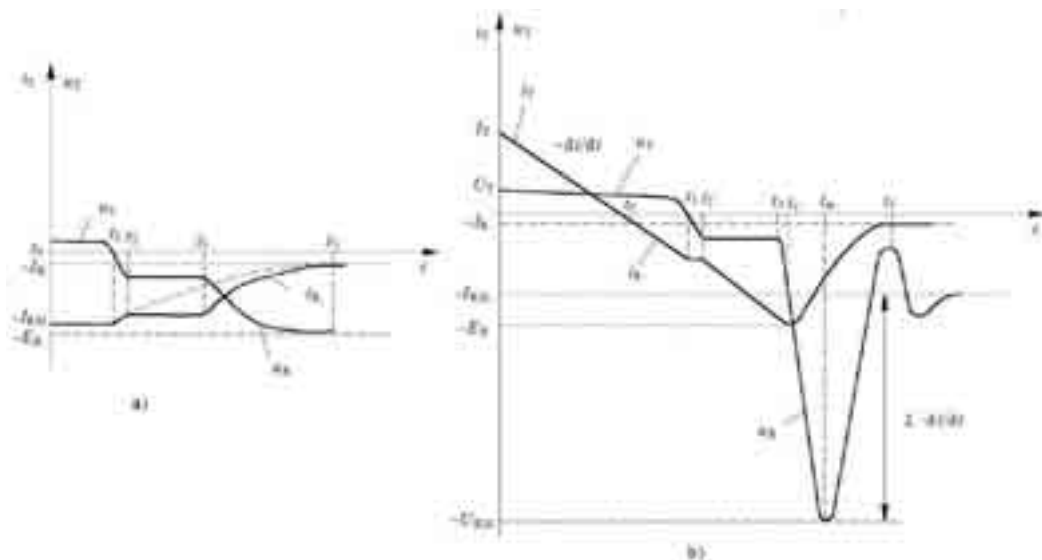
2.8.1 The transient turn-off process

The thyristor turn-off process is accompanied by the removal of the excess charge from the p-n-p-n structure, accumulated in the forward operating mode. The fastest and typical way of turning thyristors off is by voltage inversion, and the same can be done by gradually bringing current down below I_H value [4], as well as by a negative excitation current, but only with lower-powered thyristors. The subject is addressed in many works, mostly experimental ones.

For an analysis of the turn-off process the most convenient is a thyristor circuit with a purely ohmic load (Figure 1a). With voltage inversion starts the removal of excess carriers which from the bases move to external layers; transition holes from base n_1 to layer p_1 , electrons from base p_2 to layer n_2 . First removed are secondary carriers at barriers J_1 and J_3 , where a concentration gradient of secondary carriers is formed and barrier J_2 is forwardly poled, letting electron and hole currents flow through it. Hole current is dominant, because the p-base doping is stronger. Considering the fact that the lifetime of secondary carriers in p-base is shorter, that that base is narrower and that it contains a smaller quantity of secondary carriers, which, in addition to it, regenerate rather weakly across barrier J_2 , first to disappear will be the concentration gradient at barrier J_3 . At the same time, pole reversal of barrier J_3 starts; its voltage rises, thyristor current drops.

The breakdown voltage of barrier J_3 is usually low, so the breakdown occurs quickly at the moment t_2 (Figure 9a). However, as the concentration gradient of secondary carriers still exists on barrier J_1 , the constant current will go on flowing up to the moment t_3 when the concentration gradient at barrier J_1 disappears and the starting barrier layer emerges. Barrier J_1 starts with inverse polarization, gaining on thickness in the process, taking over nearly the whole external voltage. Over that period (t_3 , t_5) the thickness of the barrier layer goes up so much that thyristor resistance rises to reach several hundred k Ω , which causes current drop down to the current values of inverse polarization. In the case of an inductive circuit load, as experimentally found, this may lead to significant voltage overshoots and oscillations [32] (Figure 9b). Such voltage overshoots can cause permanent damage to thyristors [32].

In the case of an inductive circuit load, current grows linearly in intervals (t_0 , t_1) and (t_2 , t_3), because the thyristor poses a negligibly small resistance, whereas in intervals (t_1 , t_2) and (t_3 , t_5) current drops because of pole reversal, first of barrier J_3 , then of bar-



Slika 9 - Odstranjivanje suvišnog naboja iz baze tiristora
Figure 9 - Removal of excess charge from the thyristor base

U trenutku t_3 nastupa prepolarizacija barijere J_1 , struja usporava svoj rast i u t_4 postiže svoj maksimum, a napon na tiristoru poraste do vrijednosti napona izvora. Time još nije odstranjen sav suvišan naboj iz baze n, struja je još znatna, ali postupno opada do vrijednosti inverzne struje zasićenja, dok napon raste da bi u trenutku t_m poprimio svoj maksimum (slika 9b). Odgovarajuće naponsko nadvišenje jednako je padu napona na induktivitetu. Tijekom prepolarizacije barijera J_1 naglo povećava svoju debljinu, a napon brzo raste, pa pri tome u barijeri teče znatna kapacitivna struja.

Odstranjivanje suvišnog naboja iz baza ne vrši se samo inverznom strujom već i rekombinacijom, koja postaje značajnija u periodu smanjenja inverzne struje (slika 9).

2.8.2 Vrijeme oporavka

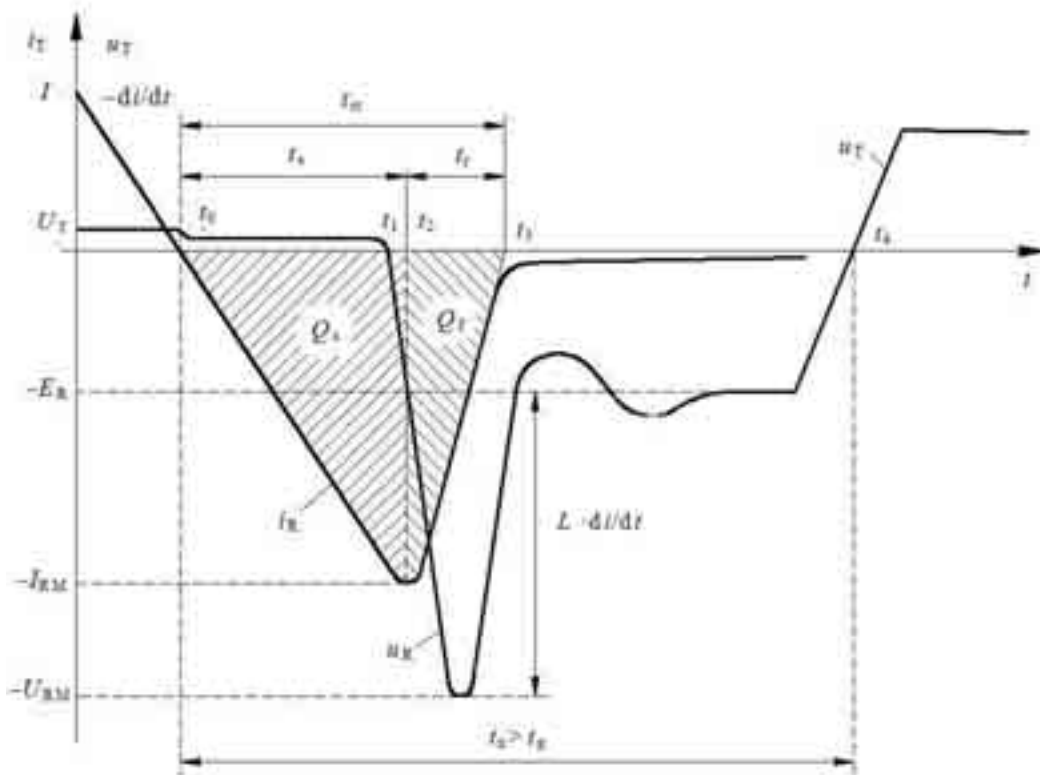
Većina tiristora građena je tako da je probojni napon barijere J_3 zanemarivo mali, pa je dinamička karakteristika isključenja tiristora praktički ista kao p-n diode (slika 10). U slučaju induktivnog opterećenja struja se linearno mijenja do trenutka t_1 , kada započinje prepolarizacija barijere J_1 (slika 10). U vremenskom intervalu t_0 do t_1 napon je pozitivan, a struja negativna, pa se tiristor može nadomjestiti naponskim izvorom čija je EMS jednaka zatečenom radnom naponu na tiristoru, a unutarnji otpor je vrlo mali. Nakon t_1 , struja još neznatno raste i u t_2 postiže svoj maksimum (slika 10). Protekli vremenski interval zove se vrijeme oporavka barijere (t_s). Zatim dolazi

rier J_1 . At the moment t_3 the pole reversal of barrier J_1 takes over, current decelerates its rise and at t_4 reaches its maximum, whereas voltage on the thyristor rises to the source voltage value. This still has not removed complete excess charge from base n, current is still significant, but gradually falling to the value of inverse saturation current, while voltage rises to reach its maximum at the moment t_m (Figure 9b). A certain voltage overshoot equals a voltage drop on inductance. In the course of pole reversal barrier J_1 rapidly increases in thickness, voltage rises quickly, and a significant capacitive current flows in the barrier.

Excess charge is removed from the bases not only by inverse current, but also by recombination which in the period of decreasing inverse current becomes more significant (Figure 9).

2.8.2 Recovery time

Most thyristors are so structured that the breakdown voltage of barrier J_3 is negligibly small, so the dynamic characteristic of thyristor turn-off is practically the same as it is with p-n diode (Figure 10). In the case of inductive load, current linearly changes up to the moment t_1 , when the pole reversal of barrier J_1 takes over (Figure 10). In the time interval t_0 to t_1 voltage is positive, current is negative, so the thyristor can be substituted for a voltage source whose EMF equals the found operating voltage on the thyristor, and the internal resistance is very small. After t_1 , current still rises slightly and at t_2 reaches its maximum (Figure 10). The passed time interval is the recovery time of barrier (t_s). Next comes n-base cleaning, where current gradually drops to the value



Slika 10 – Dinamička karakteristika isključenja tiristora
Figure 10 – The dynamic characteristic of thyristor turn-off

do čišćenja n-baze, pri čemu struja postupno opada do vrijednosti inverzne struje zasićenja. Proteklo vrijeme zove se vrijeme oporavka baze (t_f), a neki ga zovu vrijeme pada struje. Ukupno vrijeme zove se vrijeme oporavka tiristora $t_r = t_s + t_f$, dok je sa t_x označeno vrijeme odmaranja (slika 10).

Zatečena količina naboja Q_0 u n-bazi mnogo puta je veća u trenutku kad struja prelazi kroz nulu (t_0) od zatečenog naboja u p-bazi, a ovisi o parametrima tiristora, amplitudi propusne struje I i brzini smanjenja struje ($-di/dt$) (slika 10). Dio zatečenog naboja odstranjuje se rekombinacijom, a tzv. prijelazni naboj $Q_\pi = Q_s + Q_f$ putem prisile struje. Prijelazni naboj ovisi o tipu tiristora i režimu rada, a raste s temperaturom za 0,4 %/°C.

Proizvođači obično daju podatke o naboju Q_s u zavisnosti od propusne struje I , temperature i od brzine inverzne struje di_R/dt . Pomoću tih podataka može se izračunati:

$$t_s = \sqrt{\frac{2Q_0}{\frac{di_R}{dt}}}, \quad (8)$$

vrijeme oporavka barijere [t_s]:
tjemena vrijednost inverzne struje (slika 10):

of inverse saturation current. The passed time is the recovery time of barrier (t_f), some refer to it as current drop time. The total time is the thyristor's recovery time $t_r = t_s + t_f$ (Figure 10), whereas t_x signifies rest time (Figure 10).

The amount of charge Q_0 found in n-base is many time greater at the moment when current is passing through null (t_0) than the amount of charge found in p-base, depending on thyristor parameters, forward current amplitude I and current drop rate ($-di/dt$) (Figure 10). A part of the found charge is removed by recombination and the transition charge $Q_\pi = Q_s + Q_f$ due to influence exerted by current. The transition charge depends on the type of the thyristor and its operating mode, and grows with temperature at the rate of 0,4 %/°C.

Manufacturers usually disclose data on charge Q_s in dependence on forward current I , temperature and the velocity of inverse current di_R/dt . By means of these data it is possible to compute:

barrier recovery time [t_s]:
inverse current peak value (Figure 10):

$$I_{RM} = \sqrt{2Q_s \frac{di_R}{dt}} \quad (9)$$

Opadajući dio struje oporavka nije dovoljno teoretski obrađen, a eksperimentalno je utvrđeno da struja oporavka u većini slučajeva ima trokutast oblik i da je $t_s = 0,6 \cdot t_r$ [2].

U eksperimentalnim radovima [32], [34] i [50] izvršena su opširna istraživanja destruktivnih oscilacija u krugovima s diodom. Utvrđeno je da prekoračenje kritične vrijednosti di_R/dt (krug s malim otporom i relativno velikim induktivitetom) stvara nagli pad struje oporavka, pri čemu nastanu prigušene oscilacije s visokim naponskim šiljcima. Također je utvrđeno da i pri vrlo malim induktivitetima (nekoliko mikrohenrija) mogu nastati oscilacije, pa treba obratiti pozornost i na induktivitet sabirnice. Kritična brzina porasta inverzne struje tiristora proporcionalna je s debljinom n-baze.

Sprječavanje mogućih naponskih udara na tiristoru i diodi postiže se ugradnjom zaštitnog kruga.

2.8.3 Vrijeme odmaranja i ekvivalentna shema tiristora za period isključenja

Sposobnost blokiranja ponovo dovedenog pozitivnog napona tiristor postiže kad se iz n-baze odstrani sav suvišni naboj. Tijekom vremena oporavka t_{rr} odstranjen je iz n-baze samo dio suvišnog naboja, a daljnje odstranjenje odvija se pretežno rekombinacijom. Vremenski interval od prolaska struje kroz nulu pa do trenutka kada je tiristor sposoban blokirati pozitivni napon maksimalno dopuštene brzine porasta zove se vrijeme odmaranja t_x (slika 10). To vrijeme ovisi o više faktora.

Ono je proporcionalno s dužinom vremena života manjinskih nosilaca u n-bazi, koja raste s temperaturom. Zbog toga treba paziti da se pravodobno ohladi i najkraće mjesto u tiristoru, a to je početni kanal vođenja. Iz toga slijedi da vrijeme odmaranja raste s brzinom porasta struje, kao i s porastom propusne struje i dužinom njenog trajanja. Vrijeme odmaranja se skraćuje s porastom inverznog napona do određene granice, te sa smanjenjem pozitivnog napona i brzinom porasta toga napona.

Za praksu je vrlo važan proces isključenja tiristora, osobito nakon početka prepolarizacije barijere J_1 , tj. za $t > t_2$ (slika 10). U dostupnoj literaturi nije dan analitički izraz odnosa napona i struje za inverzni režim rada tiristora. Me-

The evanescent part of recovery current has not been sufficiently theoretically explored, whereas it has been experimentally found that recovery current is in most cases triangularly shaped and that $t_s = 0,6 \cdot t_r$ [2].

In experimental works [32], [34] and [50] destructive oscillations in diode circuits have been extensively explored. It has been found that excess critical value di_R/dt (a circuit with small resistance and relatively big inductance) will cause a sharp drop of recovery current, accompanied by damped oscillations with pronounced voltage spikes. It has also been found that oscillations may occur at very small inductances (several μH), so attention should also be paid to busbar inductance. The critical growth rate of thyristor inverse current is proportional to the thickness of n-base.

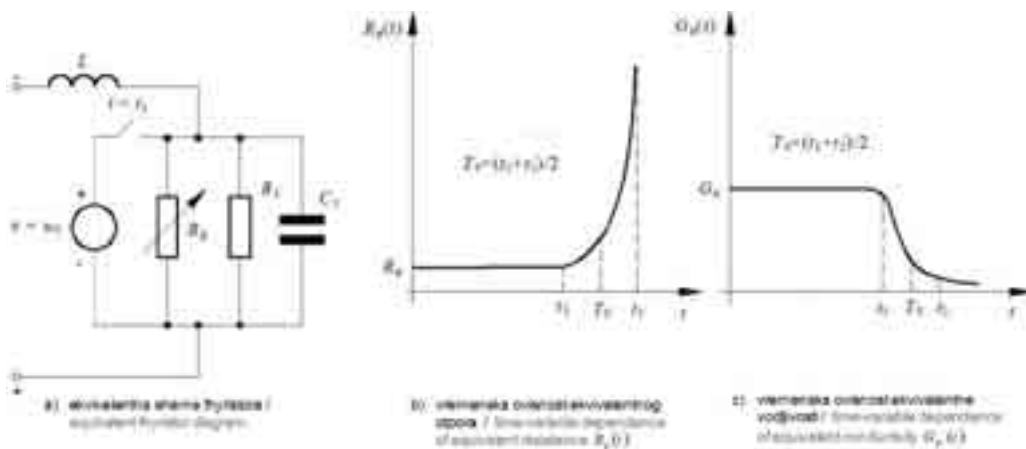
Possible voltage shocks on thyristors and diodes are prevented by installing a protection circuit.

2.8.3 The thyristor's rest time and equivalent diagram for the turn-off period

The capability of blocking a re-fed positive voltage is achieved by a thyristor when complete excess charge is removed from n-base. During the recovery time t_{rr} only a part of excess charge is removed from n-base, whereas further removal takes place largely by recombination. The time interval from the passage of current through null to the moment when the thyristor is capable of blocking the positive voltage of maximal permissible growth rate is referred to as rest time t_x (Figure 10). That time depends on a number of factors.

It is proportional to the length of the life-times of secondary carriers in n-base, which grows with temperature. Hence the need to make sure that the hottest place in the thyristor cools off in time, and that is the starting conductance channel. Therefore, the rest time grows with the growth rate of current, as well as the growth and duration of forward current. The rest time is shortened with the rise in inverse voltage up to a certain limit, as well as with the decrease in positive voltage and the rise rate of that voltage.

What matters much in practice is the thyristor turn-off process, especially after the start of the pole reversal of barrier J_1 , i.e., for $t > t_2$ (Figure 10). The available literature does not provide an analytical expression of voltage-current relation for the thy-



Slika 11 – Vrijeme odmaranja i ekvivalentna shema tiristora
 Figure 11 – Rest time and equivalent thyristor diagram

đutim, na temelju danog opisa procesa može se približno napraviti odgovarajuća nadomjesna shema.

Radi toga poslužit će pojednostavljena karakteristika prijelaznog procesa u inverznom režimu rada (slika 10). Od trenutka obrtanja napona izvora, pa do početka prepolarizacije barijere J_1 ($t = t_1$) tiristor se može nadomjestiti naponskim izvorom konstantne EMS i malog unutarnjeg otpora, ili jednostavno samo idealnim naponskim izvorom čija je EMS jednaka padu napona u tom intervalu [$e(t) = u_T$, slika 11]. Međutim, za prijelazni proces osobito je zanimljiv period od početka prepolarizacije barijere J_1 ($t \geq t_1$). Napon u vrlo kratkom vremenskom intervalu ($t_1 + t_2$) naraste na vrijednost $U \leq E_R$, a barijera se prepolarizira.

Taj period može se nadomjestiti vremenski promjenjivim otporom $R_p(t)$ (slika 11a) čija vrijednost u vrlo kratkom vremenskom intervalu (t_1, t_2) poraste od vrijednosti R_p do beskonačnosti, odnosno vodljivost se smanji od vrijednosti G_p do nule. Odgovarajući matematički model otpora $R_p(t)$ može se prikazati eksponencijalnom funkcijom:

$$R_p(t) = R_p \left(1 + e^{\frac{t-T_0}{t_2-t_1}} \right), \quad (10)$$

(slika 11a), a odgovarajuća vodljivost je (slika 11c):

$$G_p(t) = G_p \frac{1}{1 + e^{\frac{t-T_0}{t_2-t_1}}}, \quad (11)$$

Otpor $R_p(t)$ u trenutku t_2 postane reda veličine otpora R_1 inverzno polarizirane barijere J_1 . Interval (t_1, t_2) može se također nadomjestiti

ristor's inverse operating mode. However, based on the given description of the process, it is possible to approximately make an appropriate equivalent diagram.

What can serve this purpose is a simplified characteristic of the transient process in the inverse operating mode (Figure 10). From the moment of the source voltage reversal to the start of the pole reversal of barrier J_1 ($t = t_1$) the thyristor can be substituted by a voltage source of constant EMF and small internal resistance, or just by an ideal voltage source whose EMF equals the voltage drop in that interval [$e(t) = u_T$, Figure 11]. However, of special interest for the transient process is the period from the start of the pole reversal of barrier J_1 ($t \geq t_1$). In a very short time interval ($t_1 + t_2$) voltage rises to $U \leq E_R$, and the barrier reverses the poles.

That period can be substituted by time-variable resistance $R_p(t)$ (Figure 11a) the value of which increases from R_p to infinity over a very short time interval (t_1, t_2), or conductivity decreases from G_p to null. Appropriate mathematical model of resistance $R_p(t)$ can be presented by the exponential function:

(Figure 11a), whereas the corresponding conductivity is (Figure 11c):

Resistance $R_p(t)$ at the moment t_2 becomes of the order of resistance R_1 of inversely poled barrier J_1 . The interval (t_1, t_2) can also be substituted by lin-

EMS $e(t)$ linearnog porasta kao na slici 10, koja se u trenutku t_2 isključuje. U periodu $t > t_2$ glavnu ulogu ima inverzno polarizirana barijera, čija je debljina znatno porasla do trenutka t_2 . Taj period rada može se nadomjestiti paralelnim spojem otpora i kapaciteta inverzno polarizirane barijere J_1 (slika 11a). Dok je otpor $R_p(t)$ u tom intervalu naglo poprimio neizmjerne vrijednosti. Na isti način kao u točki 2.4, otpor i kapacitet barijere J_1 može se linearizirati.

3 ZAKLJUČAK

Analizirana su dinamička svojstva tiristora. Prvo su razmatrana dinamička svojstva i karakteristike uključivanja, a zatim je detaljnije analiziran efekt di/dt . Na temelju proučenih svojstava širenja uključenog kanala predložena je, za taj režim rada, nadomjesna shema tiristora u vidu vremenski promjenjivog otpora. Na temelju općeg izraza za računanje toga otpora određen je odgovarajući izraz za tiristor s prstenastom i centralnom pobudom. Zatim je analiziran efekt du/dt i predložena adekvatna nadomjesna shema za taj period rada. Na kraju su analizirana dinamička svojstva isključenja tiristora i također predložena odgovarajuća nadomjesna shema.

early rising EMF $e(t)$, as in Figure 10, which turns off at the moment t_2 . In the period $t > t_2$ the main role is played by the inversely poled barrier, the thickness of which has considerably increased up to the moment t_2 . That period of operation can be substituted by a parallel connection of the resistance and capacity of the inversely poled barrier J_1 (Figure 11a), while resistance $R_p(t)$ in that interval rapidly rose to infinity. The resistance and capacity of barrier J_1 can be linearized in the same way as in section 2.4 above.

3 CONCLUSION

In this work the dynamic properties of thyristors are analyzed. Considered first were the dynamic turn-on properties and characteristics, which was followed by a more detailed account of the di/dt effect. Based on the studied propagation properties of a turned-on channel, the thyristor's substitution diagram was proposed for this operating mode in the form of time-variable resistance. On the basis of the general expression for the calculation of this resistance, an appropriate expression for the thyristor with ring-shaped and central excitation was defined. Then the du/dt effect was analyzed and an appropriate substitution diagram proposed for that operating period. Finally, the thyristor's dynamic turn-off properties were analyzed and an appropriate substitution diagram likewise proposed.

LITERATURA / REFERENCES

- [1] GENTRY, . et al., Semiconductor Controlled Rectifiers, by Prentice-Hall, 1964
- [2] Тиристоры (справочник), Энергия, 1971
- [3] КУЗЬМИН, ., Тиристоры малой и средней мощности, Советско радио, Москва, 1970
- [4] JUZBAŠIĆ, ., Elektronički elementi, Tehn. knjiga, Zagreb, 1970.
- [5] MEYR, ., Thyristoren in der technischen Anwendung, Band 1, Berlin, 1967
- [6] ДЗЮБИН, ., Тиристоры в электрических схемах, Энергия, Москва, 1972
- [7] ИСАКОВ, . et al., Тиристорные преобразователи повышенной частоты, Техника, Киев, 1976
- [8] STUMPE, ., ETZ-A 83 4, 1962
- [9] GERLACH, ., AEG – Mitteilungen 51, 11/12, 1961
- [10] GERLACH, S., ETZ-A 83, 8, 1962
- [11] ANWANDER, B.B., Mitteilungen 53, 10, 1966
- [12] BORCHERT, ., STUMPE, A.C., AEG-Mitteilungen 54, 5/6, 1964
- [13] FUKSA, ., Elektrotech. Obzor 63, 11, 1974
- [14] КАРДО-СЫСОЕВ, . et al, Ф.Т.П. 8, 6, 1974
- [15] GIBBONS, ., IEEE Trans. E D-11., 8, 1964
- [16] GENTRY, ., IEEE Trans. E D-11, 2, 1964
- [17] YANG, ., SKALNIK, ., IEEE Trans. E D-14, 8, 1967
- [18] GIBBONS, ., Proc. IEEE 55, 8, 1967
- [19] КУЗЬМИН, . et al, Радиот. и электр., 7, 1963
- [20] НАУМОВ, . et al, Радиот. и электр. , 9, 1965
- [21] ЛЕБЕДЕВ, ., Радиотех и электр. , 8, 1966
- [22] BURTSCHER, ., SPENKE, ., Siemens Forsch. u. Entwickl. Ber., 3, 4, 1974
- [23] ЧЕЛНКОВ, . et al, Радиот. и электр. , 12, 1966
- [24] КУЗЬМИН, . et al, Радиот. и электр., 1, 1967
- [25] ЛЕБЕДЕВ, ., Радиот. и электр., 4, 1967
- [26] КУЗЬМИН, . et al, Радиот. и электр., 4, 1968
- [27] КУЗЬМИН, . et al, Радиот. и электр., 9, 1968
- [28] ГОМОНОВА, . et al, Радиоэлектр., XIV, 1, 1961
- [29] ДУМАНЕВИЧ, ., Радиот. и электр., 11, 1972
- [30] КӦНЛ, ., Scientia electr. ,11, 7, 1965
- [31] SOMOS, ., Communications and Electronics 4, 7, 1961
- [32] 31/1 ДЕРМЕНХИ, . et al, Радиот. и электр., 18, 4, 1973
- [33] СИТНИК, . et al, Электромеханика 8, 1966
- [34] STUMPE, ., ETZ-A 83, 9, 1962
- [35] ДЕРМЕНЖИ, . et al, Радиот. и электр., 15, 9, 1970
- [36] КОЦЮБА, ., Тр. Лит. пол. инст., No 327, 1972
- [37] КУЗЬМИН, . et al, Радиот. и электр., 20, 8, 1975
- [38] JAESKLIN, ., IEEE Tr., ED-23, 8, 1976
- [39] DISKOPF, ., ETZ-A 89, 6, 1968
- [40] КАРДО-СЫСОЕВ, ., Радиот. и электр., 15, 1, 1970
- [41] МОЛИБОГ, . et al, Радиот. и электр., 18, 4, 1973
- [42] МОЛИБОГ, . et al, Радиот. и электр., 16, 6, 1971
- [43] КУЗЬМИН, . et al, Радиот. и электр., 18, 1, 1973
- [44] ПАВЛИК, . et al, Радиот. и электр., 18, 7, 1973
- [45] КАРДО-СЫСОЕВ, ., Ф.Т.П. , 5, 12, 1971
- [46] ДЕРМЕНЖИ, . et al, Радиот. и электр., 7, 1970
- [47] ГРЕХОВ, . et al, Ф.Т.П., 4, 11, 1970
- [48] МАРНАН, ., Electronics 35, Au 17, 1962
- [49] МАРНАН, ., IEEE Trans. Comm. a. Electr., 83, Sep. 1964
- [50] LONGINI, ., IEEE Trans. ED-10, May, 1963
- [51] KUZMANOVIĆ, B., Analiza prenapona oporavka energetskih ventila u omskoinduktivnom krugu, Automatika 1/2, Zagreb, 1989.
- [52] KUZMANOVIĆ, B., Uključenje tiristora i period širenja vodljivog kanala, „Elektrotehnika“, 2, Zagreb, 1988.
- [53] KUZMANOVIĆ, B., Analiza brzine porasta napona na inverzno polariziranoj poluvodičkoj barijeri u omsko-induktivnom krugu, „Elektrotehnika“ 32, 2, Zagreb, 1989.
- [54] KUZMANOVIĆ, B., Destruktivne oscilacije na poluvodičkoj diodi u krugu malog induktiviteta, „Elektrotehnika“ 32, 6, Zagreb, 1989

- [55] KUZMANOVIĆ, B., Statička i dinamička svojstva tiristora, Radovi TVA br. 20, monografija, Zagreb, 1978.
[56] KUZMANOVIĆ, B., Destructive Oscillations in Low Inductance Diode Circuit, Proceedings of the IEEE Industry Applications Society Annual Conference, San Diego, USA, 1989

Adresa autora: Address of author:

Prof. dr. sc. Branislav Kuzmanović Novački vidikovac 6 10060 Zagreb Hrvatska	Prof Branislav Kuzmanović , PhD Novački vidikovac 6 10060 Zagreb Croatia
Dr. sc. Zoran Baus SIEMENS d.d. Heinzelova 70a 10000 Zagreb Hrvatska	Zoran Baus , PhD SIEMENS d.d. Heinzelova 70a 10000 Zagreb Croatia

Uredništvo primilo rukopis:
2008-06-10

Manuscript received on:
2008-06-10

Prihvaćeno:
2008-09-16

Accepted on:
2008-09-16

UPUTE AUTORIMA

UPUTSTVO ZA RUKOPIS

1. Časopis Energija objavljuje članke koji do sada nisu objavljeni u nekom drugom časopisu.
2. Radovi se pišu na hrvatskom ili engleskom jeziku, u trećem licu, na jednoj stranici papira, počinju s uvodom i završavaju sa zaključkom. Stranice se označavaju uzastopnim brojevima.
3. Radovi u pravilu ne mogu biti dulji od 14 stranica časopisa Energija (oko 9000 riječi).
4. Ime i prezime autora, znanstvena ili stručna titula, naziv i adresa tvrtke u kojoj autor radi i e-mail adresa navode se odvojeno.
5. Iznad teksta samoga rada treba biti sažetak od najviše 250 riječi. Sažetak treba biti zaokružena cjelina razumljiva prosječnom čitatelju izvan konteksta samoga rada. Nakon sažetka navode se ključne riječi.
6. Članci se pišu u Word-u sa slikama u tekstu ili u posebnim file-ovima u tiff formatu, 1:1, rezolucije namanje 300 dpi.
7. Članci se pišu bez bilješki na dnu stranice.
8. Matematički izrazi, grčka slova i drugi znakovi trebaju biti jasno napisani s dostatnim razmacima.
9. Literatura koja se koristi u tekstu navodi se u uglatoj zagradi pod brojem pod kojim je navedena na kraju članka. Korištena literatura navodi se na kraju članka redom kojim je spomenuta u članku. Ako rad na koji se upućuje ima tri ili više autora, navodi se prvi autor i potom et al. Nazivi časopisa navode se u neskrćenom obliku.

Časopis

- [1] FRAZIER, L., FODOR, J. D., The sausage machine: A new two-stage parsing model. *Cognition*, 6 (1978)

Knjiga

- [2] NAGAO, M., Knowledge and Inference, Academic Press, Boston, 1988

Referat

- [3] R. L. WATROUS, L. SHASTRI Learning phonetic features using connectionist networks: An experiment in speech recognition. Presented at the Proceedings of the IEEE International Conference on Neural Networks, (1987) San Diego, CA

Neobjavljeno izvješće/teza

- [4] J. W. ROZENBLIT A conceptual basis for model-based system design, PhD. Thesis, Wayne State University, Detroit, Michigan, 1985

10. Članak je prihvaćen za objavljivanje ako ga pozitivno ocijene dva stručna recenzenta. U postupku recenzije članci se kategoriziraju na sljedeći način:
 - izvorni znanstveni članci – radovi koji sadrže do sada još neobjavljene rezultate izvornih istraživanja u potpunom obliku,
 - prethodna priopćenja – radovi koji sadrže do sada još neobjavljene rezultate izvornih istraživanja u preliminarnom obliku,
 - pregledni članci – radovi koji sadrže izvoran, sažet i kritički prikaz jednog područja ili njegova dijela u kojem autor i sam aktivno sudjeluje – mora biti naglašena uloga autorovog izvornog doprinosa u tom području u odnosu na već objavljene radove, kao i pregled tih radova,
 - stručni članci – radovi koji sadrže korisne priloge iz struke i za struku, a ne moraju predstavljati izvorna istraživanja.
11. Članci se lektoriraju i provodi se metrološka recenzija.
12. Članci se dostavljaju u elektroničkom obliku i 1 primjerak u tiskanom obliku na adresu:
Hrvatska elektroprivreda d.d.
N/r tajnika Uređivački odbor – mr. sc. Slavica Barta-Koštrun
Ulica grada Vukovara 37, 10000 Zagreb, Hrvatska
Tel.: +385 (1) 632 2641
Faks: +385 (1) 6322143
e-mail: slavica.barta@hep.hr

KOREKTURA I AUTORSKI PRIMJERC I

1. Autori su dužni izvršiti korekturu svoga rada prije objavljivanja. Veće promjene teksta u toj fazi neće se prihvatiti.
2. Autori dobivaju besplatno 5 primjeraka časopisa u kojemu je objavljen njihov članak. Naknada za objavljeni članak obračunava se prema Odluci o visini autorskih honorara časopisa Energija.

AUTORSKO PRAVO

1. Autorsko pravo na sve objavljene materijale ima časopis Energija.
2. Autori moraju telefaksom dostaviti popunjeni obrazac o autorskom pravu nakon prihvaćanja članka.
3. Autori koji žele koristiti materijale koji su prethodno objavljeni u časopisu Energija trebaju se obratiti izdavaču.

MANUSCRIPT REQUIREMENTS

- 1 Energy journal publishes articles never before published in another periodical.
- 2 Articles are written in Croatian or English, in the third person, on one paper side, beginning with an introduction and ending with a conclusion. Pages are numbered consecutively.
- 3 As a rule articles cannot exceed 14 pages of the Energija journal (about 9 000 words).
- 4 The name of the author and his/her academic title, the name and address of the company of the author's employment, and e-mail address, are noted separately.
- 5 The text of the article is preceded by a summary of max. 250 words. The summary is followed by the listing of the key words.
- 6 Article are written in MS Word with pictures embedded or as separate TIFF files, 1:1, min. 300 dpi.
- 7 Articles are written without bottom of page footnotes.
- 8 Mathematical expressions, Greek letters and other symbols must be clearly written with sufficient spacing.
- 9 The sources mentioned in the text of the article are only to be referenced by the number, in the square brackets, under which it is listed at the end of the article. References are listed at the end of the article in the order in which they are mentioned in the text of the article. If a work referenced has three or more authors, the first author is mentioned followed by the indication et al. Names of journals are given in full.

Journal

- [1] FRAZIER, L., FODOR, J. D., The sausage machine: A new two-stage parsing model, *Cognition*, 6 (1978)

Book

- [2] NAGAO, M., *Knowledge and Inference*, Academic Press, Boston, 1988

Paper

- [3] R. L. WATROUS, L. SHASTRI Learning phonetic features using connectionist networks: An experiment in speech recognition. Presented at the Proceedings of the IEEE International Conference on Neural Networks, (1987) San Diego, CA

Unpublished report/theses

- [4] J. W. ROZENBLIT A conceptual basis for model-based system design, PhD. Thesis, Wayne State University, Detroit, Michigan, 1985

- 10 An article will be accepted for publishing if it is positively evaluated by two reviewers. In the review, articles are categorized as follows:
 - original scientific papers – works containing hitherto unpublished full results of original research,
 - preliminary information – works containing hitherto unpublished preliminary results of original research,
 - review papers – works containing the original, summarised and critical review from the field or from a part of the field in which the author of the article is himself/herself involved – the role of the author's original contribution to the field must be noted with regard to already published works, and an overview of such works provided,
 - professional articles – works containing useful contributions from the profession and for the profession not necessary derived from original research.
- 11 Articles will undergo language editing and metrological reviews will be language-edited and reviewed for metrology.
- 12 Article are to be submitted in a machine-readable form plus one printout to the following address: electronic form along with 1 hard copy to :
 - HEP d.d. – Energija
 - Attn. Secretary to Editorial Board – Slavica Barta-Koštrun, MSc
 - Ulica grada Vukovara 37, 10000 Zagreb, Hrvatska
 - Tel.: +385 (1) 632 2641
 - Fax: +385 (1) 6322143
 - e-mail: slavica.barta@hep.hr

CORRECTIONS AND FREE COPIES FOR AUTHORS

1. Authors are required to make the corrections in their works prior to publication. Major alterations of the text at the stage of publication will not be accepted.
2. The authors will receive 5 free copies of the Journal in which their respective articles APPEAR. The fee for an article published will be calculated in accordance with the Decision on the Fees for the Authors of the Energija journal.

COPYRIGHT

1. The copyright on all the materials published belongs to the Energija journal.
 2. Authors must fax in a filled out copyright form when their articles have been accepted.
 3. Authors wishing to use the materials published in the Energija journal need to contact the publisher.
-

INSTRUCTIONS TO AUTHORS



Energetski sustav neke zemlje ima zadatak kvalitetno opskrbljivati električnom energijom sve potrošače koji su na njega priključeni. Osnovna kvaliteta takvog sustava visoka je raspoloživost dobave električne energije reda 99,9 % i višeg.

Elektroenergetski sustav nije slučajni skup pojedinačnih međusobno neovisnih elemenata (elektrane, visokonaponski vodovi i postrojenja, niskonaponske mreže), već je usklađen i međuovisni sustav koji je razvijan, građen, korišten i održavan u polazno definiranom smislu.

Sadržaj knjige namijenjen je svim stručnim osobama iz područja elektroenergetike koji su već uključeni u sustav projektiranja, građenja i održavanja dalekovoda ili se tek žele uključiti u tu djelatnost bilo kao planeri, projektanti, graditelji i korisnici dalekovoda. Kroz pojedina poglavlja namjera je autora približiti svu opsežnost aktivnosti, postupaka i radnji koje su neophodne u fazi pripreme, projektiranja i gradnje dalekovoda stručnim kadrovima koji su svoj poslovni život posvetili toj djelatnosti.