ENERGIJA

JOURNAL OF ENERGY

04/09

ENERGIJA

IZDAVAČ
Hrvatska elektroprivreda d.d., Zagreb

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

ZA IZDAVAČA
Leo Begović, dipl. ing.

POMOĆ U IZDAVANJU
Ministarstvo znanosti, obrazovanja i športa

UREĐIVAČKI SAVJET
Mr. sc. Kažimir Vrankić, (predsjednik), Zagreb – doc. dr. sc. Ante Ćurković, 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 –CIKLOPEA, Zagreb

UREDNIŠTVO I UPRAVA
HEP d.d. – Energija, Uređivački odbor
Ulica grada Vukovara 37, 10000 Zagreb, Hrvatska
Telefoni: +385 (1) 632 2531 i 6322641
Telefaks: +385 (1) 632 2143
e-mail: goran.slipac@hep.hr; slavica.barta@hep.hr
www.hep.hr

Godišnje izlazi 6 brojeva.
Godišnja pretplata bez PDV-a (10 %) iznosi:
– za pojedince 275 kn,
– za poduzeća 440 kn,
– za studente 65 kn.
Žiro račun kod Zagrebačke banke broj:
2360000-1400129978

Godišnja pretplata za inozemstvo iznosi USD 95.
Devizni račun:
Zagrebačka banka broj: 2000006299

Grafičko uređenje omota – mr. sc. Kažimir Vrankić, Zagreb
Grafičko uređenje časopisa – Bestias dizajn d.o.o., Zagreb
Tisak – Tiskara Zelina d.o.o.,

Naklada – 1 500 primjeraka
Godište 58(2009)
Zagreb, 2009
Broj 4., str. 329-448

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

ENERGIJA

PUBLISHED BY
Hrvatska elektroprivreda d.d., Zagreb

CO-PUBLISHED BY
University of Zagreb, Fakulty of Electrical Engineering and Computing Ministry of Economy, Labour and Entrepreneurship

PUBLISHER'S REPRESENTATIVE
Leo Begović, dipl. ing.

SUPPORTED BY
Ministry of Science, Education and Sport

EDITORIAL COUNCIL
Kažimir Vrankić, MSc, (Chairman), Zagreb – Assistant Prof Ante Ćurković, 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 – CIKLOPEA, Zagreb

HEAD OFFICE AND MANAGEMENT
HEP d.d. – Energija, Editorial Board
Ulica grada Vukovara 37, 10000 Zagreb, Hrvatska
Telephone: +385 (1) 632 2531 and 6322641
Fax: +385 (1) 632 2143
e-mail: goran.slipac@hep.hr; slavica.barta@hep.hr
www.hep.hr

Appears 6 times a year.
Annual subscription fee excl. VAT (10 %)
– for individuals HRK 275,
– for companies HRK 440,
– for students HRK 65.
Number of gyro account with Zagrebačka banka
2360000-1400129978

Annual subscription fee for Y overseas: USD 95.
Number of forign currency account wit Zagrebačka banka:
2000006299

Cover design – Kažimir Vrankić, MSc, Zagreb
Graphic layout – Bestias dizajn d.o.o., Zagreb
Printed by – Intergrafika d.o.o., Zagreb

Circulation – 1 500 copies
Volume 58(2009)
Zagreb, 2009
No. 4, pp. 329-448

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

SADRŽAJ

Časopis je ubilježen u Ministarstvu znanosti, obrazovanja i športa pod brojem 161 od 12.11.1992.

Časopis je indeksiran u sekundarnom bibliografaskom izvoru INSPEC – The Institution of Electrical Engineering, England.

CONTENTS

The journal is registered with the Ministry of Science, Education and Sport under No. 161 since 12.11.1992

The 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 Vama je i četvrti broj časopisa Energija u 2009. godini. Razdoblje recesije, odnosno smanjenje gospodarske aktivnosti značajno utječe i na energetski sektor, bilo da se smanjuje potrošnja energije, bilo da se smanjuju investicije u izgradnju novih energetskih objekata. Suprotno ovomu, analitičari i stručnjaci ne smanjuju aktivnosti na analizama i planiranju razvoja energetskog i elektroenergetskog sektora jer će, sasvim je izvjesno, vrlo brzo doći razdoblje intenzivnijeg investiranja i razvoja gospodarstva, što za energetski sektor znači potrebu dobave novih količina energije. Ne treba osobito naglašavati kako je kraj kalendarske godine vrijeme kada se stručnjaci obično bave planiranjem razvoja, pa držimo da je to upravo prigoda da nam se pridružite svojim radovima na ovim i sličnim temama.

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

— Mogućnosti razvoja elektroenergetskog sektora Bosne i Hercegovine,
— Energetska certifikacija zgrada i suvremeni energetski koncepti,
— Potrošnja energije električne željeznice,
— Analiza podešenja distantne zaštite provedbom primarnih pokusa,
— Analiza kutne stabilnost sinkronog generatora u ovisnosti o izboru sustava uzbude.

Prvi članak u ovom broju časopisa Energija donosi nam stanje i perspektive elektroenergetskog sektora u Bosni i Hercegovini koji je u relativno specifičnoj situaciji. Radi se o tri elektroprivredna poduzeća, u dva entiteta u jednoj državi sa zajedničkim ciljem ispunjenja obveze namirenja potreba za električnom energijom. Specifičnost ovog složenog slučaja je, za prilike koje vladaju u Bosni i Hercegovini, relativno velik potencijal izgradnje termoelektrana na ugljen te obnovljivih izvora energije (malih elektrana raznih tehnologija kao i velikih hidroelektrana). U slučaju izgradnje svih raspoloživih potencijalnih kandidata, sigurno je da bi elektroenergetska bilanca pokazivala značajne viškove električne energije koji bi se mogli izvoziti u regiju. Ipak, autor sugerira optimiranje izgradnje, ali i pogona elektrana na razini Bosne i Hercegovine, čime bi se postigao optimum na razini sva tri elektroprivredna poduzeća zajedno. Ključno je pitanje, hoće li do toga doći i je li to uopće moguće postići.

Drugi članak opisuje sustav uvođenja energetske certifikacije zgrada u hrvatsko zakonodavstvo te način certificiranja zgrada u energetske razrede prema godišnjoj potrebnoj toplinskoj energiji za grijanje. Implementacijom EU Direktive 2002/91/EC o energetskim svojstvima zgrada u hrvatsko zakonodavstvo uvodi se obvezna energetska certifikacija zgrada za nove i postojeće zgrade, a implementira se temeljem Akcijskog plana za implementaciju izrađenog u Ministarstvu zaštite okoliša, prostornog uređenja i graditeljstva (MZOPUG) i usvojenog u travnju 2008. godine. U članku se iskazuju

Dear readers!

Before you is another, fourth edition of Energija for the year 2009. The period of recession, that is, reduced economic activity, significantly impacts the energy sector, which is evidenced by the reduction in both energy consumption and in the investments in the construction of new energy facilities. Contrary to this, analysts and experts do not reduce their activities on analyses and planning of the development of the energy and electric power system because the time of more intense investment and economy growth will surely come and it will bring the need for supplying new amounts of energy to the electric power sector. It is not necessary to particularly stress that the end of the calendar year is a time when experts are usually involved in planning development so we believe that that is exactly the right occasion for you to join us with your papers on these and similar subjects.

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

— Possibilities for the development of the electric power sector of Bosnia and Herzegovina,
— Energy certification of buildings and contemporary energy concepts,
— Electric railway energy consumption,
— Distant protection setting analysis by primary trials,
— Analysis of the synchronous generator angular stability depending on the choice of the excitation system.

The first article of this issue of Energija presents us with the condition and perspectives of the electric power sector in Bosnia and Herzegovina, which is in a relatively specific situation. The matter at hand are three electric power companies, in two entities in one state with the common obligation of settling the needs for electric power. A specificity of this complex case is, for the current circumstances in Bosnia and Herzegovina, a relatively large potential for the construction of coal-fuelled thermal power plants and renewable energy sources (small power plants of different technologies as well as large hydroelectric plants). In case of construction of all the available potential candidates, it is probable that the electric power balance would show significant surpluses of electric power which could be exported into the region. However, the author suggests optimizing the construction as well as the power plant drives at the level of Bosnia and Herzegovina which would provide for the optimum at the level of all three companies together. The key question is whether that will take place and if it can be achieved at all.

The second article describes the system for the introduction of energy certification of buildings into the Croatian legislature and the manner of classification of buildings into energy classes according to the thermal energy required for heating at the annual level. By implementing the EU Directive 2002/91/EC on energy performances of buildings into the Croatian legislature, obligatory certification of buildings is introduced for new and existing buildings and it is implemented based on the Action Plan for Implementation composed in the Ministry of Environmental Protection, Physical Planning and Construction (MZOPUG) and adopted in April 2008. The article states the expectations that energy certification of buildings, undertaken and implemented at a high-quality level, will play a key role in the improveočekivanja kako će Energetska certifikacija zgrada, kvalitetno provedena i implementirana, odigrati ključnu ulogu u podizanju kvalitete gradnje i kvalitetnom osmišljavanju energetskog koncepta novih zgrada, pokretanju sustavne obnove i osuvremenjivanja postojećeg sektora zgrada te značajno pridonijeti razvoju integralnog projektiranja, uzimajući u obzir cijeli životni vijek zgrade.

Treći članak opisuje ponašanje elektrovuče na željeznici koja predstavlja specifičnog potrošača elektroenergetskog sustava. Nema sumnje kako je optimiranje potrošnje električne energije elektrovuče određeni vid uštede, ne samo u smislu smanjenja potrošnje, nego i ušteda u elektroenergetskom sustavu smanjenjem nepovoljnog utjecaja na ostali dio elektroenergetskog sustava. U radu je prikazan algoritam za simulaciju kretanja vlakova kojim se određuje najprije mehanička, a potom i električna snaga potrebna za vuču. Uz model za simulaciju kretanja vlaka u članku je prikazana analiza utjecajnih faktora na potrošnju električne energije za elektromotorni vlak koji prometuje na hrvatskim prigradskim željeznicama. Rezultati dobiveni algoritmom za simulaciju kretanja vlaka i elektrovučnim proračunom uspoređeni su s izmjerenim pa je pokazano da se izračunate struje i naponi relativno dobro podudaraju s mjerenim strujama napojnih vodova i napona u elektrovučnoj podstanici.

Četvrti članak donosi jedan vrlo zanimljiv aspekt ispitivanja djelovanja relejne zaštite. Na području zapadnog dijela elektroenergetskog sustava (EES-a) Hrvatske rekonstruirani su vodovi prijenosne mreže radi poboljšanja sigurnosti i kvalitete pogona. Specifičnost razmatranog dijela EES-a je da u okruženju postoji samo jedan snažni izvor napajanja; termoelektrane Plomin 1, na naponskoj razini 110 kV, i Plomin 2, na naponskoj razini 220 kV, smještene na istoj lokaciji. Kvar nastao u razmatranoj mreži napaja se gotovo isključivo iz jedne pojne točke. Navedeni nerazmjer u distribuciji struja kvara nerijetko rezultira pojavom takvih uvjeta koji ne jamče ispravno djelovanje zaštitnih releja na vodovima.U radu su opisani pripremni radovi i sama provedba primarnih pokusa na T-spoju 110 kV voda termoelektrane Plomin - transformatorske stanice Šijana i Vinčent. Ispitivanjem provedenim sekundarnim injektiranjem analognih vrijednosti (ispitivanje s kraja na kraj) pokazalo se da sustav radi ispravno, ali se tijekom pravog kvara pokazalo kako stanje nije potpuno zadovoljavajuće, jer ulazne vrijednosti potrebne za ispitivanje (naponi i struje) nisu bile jednake vrijednostima koje su se javile tijekom pravog kvara.

U zadnjem, petom članku u ovom broju časopisa Energija, donosimo opis matematičkog modela elektroenergetskog sustava s više sinkronih generatora u kojemu su generatori predstavljeni nelinearnim matematičkim modelom. Primjenom takvog modela istražen je utjecaj načina napajanja sustava uzbude na kutnu stabilnost generatora u uvjetima pojave kratkog spoja u mreži. Postavljeni model omogućuje analizu stabilnosti generatora u uvjetima velikih poremećaja u elektroenergetskom sustavu za slučaj generatora s nezavisnom uzbudom i generatora sa samouzbudom. Rezultati istraživanja mogu poslužiti prilikom donošenja odluke o izboru tipa uzbude generatora, pri obnovi postojećih i izgradnji novih generatora.

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

ment of construction quality and quality designing of the energy concept of new buildings, launching systematic renovation and contemporizing the existing building sector, and also significantly contribute to the development of integral engineering, taking into consideration the entire building's lifespan.

The third article describes the behaviour of the electric traction on a railway which represents a specific consumer of the electric power system. There is no doubt that optimizing of the electric power consumption of the electric traction is a certain aspect of savings, and that not only in the sense of reduced consumption but also as savings in the electric power system by reducing the unfavourable effect on the remaining part of the electric power system. The work shows the algorithm for simulation of the trains' movement which serves to determine firstly the mechanical and then also the electric power required for traction. Besides the train movement simulation model, the article also shows the analysis of impact factors on the electrical power consumption for the electromotor train which travels the Croatian suburban rails. The results obtained by the algorithm for train movement simulation and by the electric traction calculation are compared with the measured results and this reveals that the calculated currents and voltages coincide relatively well with the measured currents of the supply lines and the voltages on the side of the electric traction substation.

The fourth article brings one very interesting aspect of testing the effect of relay protection. In the territory of the western part of the Croatian electric power system (EPS) lines of the transmission network have been reconstructed for the purpose of improvement of safety and drive quality. A specificity of the observed part of the EPS is that in the environment there is only one powerful supply source; Plomin 1 thermal power plant at the voltage level of 110 kV and Plomin 2 at the voltage level of 220 kV, which are in the same location. The fault which occurred in the observed network is charged almost entirely from one supply point. The stated disproportion in the distribution of fault currents often results in the occurrence of such conditions which do not guarantee proper functioning of the protection relays on the lines. The paper describes the preparatory works and the very implementation of primary trials on the T-junction of the 110 kV line of the thermal power plants Plomin - Šijana and Vinčent transformer stations. The trials performed by secondary injection of analogous values (end-to-end trial) showed that the system worked properly but during the real fault it was revealed that it was nevertheless not completely satisfactory because input values necessary for the trial (voltages and currents) were not equal to the values which occurred during the real fault.

In the last, fifth article of this issue of Energija, we present a description of the mathematical model of the electric power system with several synchronous generators and in which the generators are presented by a non-linear mathematical model. By applying such a model, the impact of the manner of supplying the excitation system on the angular stability of the generator was researched in the circumstances of occurrence of a short circuit in the network. The established model enables the analysis of the generator's stability in the circumstances of great disruptions in the electric power system for the case of the generator with independent excitation and the generator with self-excitation. Research results can be useful when making the decision on the choice of the generator excitation type, upon renewal of the existing and building of new generators.

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

Editor-in-chief:
Goran Slipac, MSc

MOGUĆNOSTI RAZVOJA ELEKTROENERGETSKOG SEKTORA BOSNE I HERCEGOVINE

THE POSSIBILITIES FOR THE DEVELOPMENT OF THE ELECTRIC POWER SECTOR OF BOSNIA AND HERZEGOVINA

Mladen Zeljko, Zagreb, Hrvatska

U članku se iznosi pregled stanja i perspektive razvoja elektroenergetskog sektora Bosne i Hercegovine (BiH) do 2020. godine [1]. Uvažavajući postojeću organizacijsku strukturu elektroenergetskog sektora, dan je pregled projekcija potrošnje električne energije po elektroprivredama, entitetima i za BiH kao cjelinu. Zatim su opisani postojeći elektroenergetski (proizvodni) objekti te najizglednije elektrane-kandidati za izgradnju u sljedećem desetljeću. Također je napravljena prosudba mogućnosti izvoza električne energije u zemlje okruženja.

This article overviews the existing condition and the development perspectives for the electric power sector of Bosnia and Herzegovina (BiH) until 2020 [1].

Acknowledging the existing organisational structure of the electric power sector, an overview of electricity consumption projections is given per electric utility company, per entity and for Bosnia and Herzegovina as a whole. It is followed by descriptions of existing electric power (production) facilities, and the power plant candidates for construction in the following decade. An estimate of electricity export possibilities into neighbouring countries has also been made.

Ključne riječi : elektrane-kandidati za izgradnju; izgradnja elektrana; izvoz električne energije; postojeće elektrane; potrošnja električne energije; proizvodnja električne energije

Keywords: candidate power plants; electricity consumption; electricity production; existing power plants; export of electricity; power plant construction

1 UVOD

Slučaj elektroenergetskog sektora BiH je vrlo specifičan s obzirom na ustavno ustrojstvo same države. Postoje tri elektroprivrede: JP Elektroprivreda Bosne i Hercegovine d.d. Sarajevo (EP BiH), JP Elektroprivreda Hrvatske zajednice Herceg Bosne d.d. Mostar (EP HZHB) te Elektroprivreda Republike Srpske a.d. (EP RS)), od kojih je svaka odgovorna za određeni teritorij u smislu podmirivanja potrošnje električne energije. Dodatno situaciju usložnjava Distrikt Brčko, u kojem postoji zasebno tijelo povezano s lokalnom vladom, koje obavlja djelatnost distribucije električne energije.

1 INTRODUCTION

The electric power sector is very specific as regards the constitutional structure of Bosnia and Herzegovina. There are three electric utility companies (Public Electric Power Company of Bosnia and Herzegovina d.d. Sarajevo (EP BiH), Public Electric Power Company of the Croatian Community of Herzeg-Bosnia d.d. Mostar (EP HZHB), and the Power Utility of the Republic of Srpska a.d. (EP RS)) and each is responsible for a certain territory in the sense of meeting the needs for electricity consumption. The situation is made more complex by the Brčko District which has an independent body associated with the local government and which performs the electricity distribution services.

2 PREDVIĐENA POTROŠNJA ELEKTRIČNE ENERGIJE

U skladu s najboljom praksom (primjenom MAED modela) urađeno je predviđanje svih oblika energije, dakle i električne energije, posebno za svaku elektroprivredu, zatim za svaki entitet i konačno za BiH kao cjelinu. U nastavku su prikazane tablice koje sadrže podatke o potrošnji električne energije, vršnom opterećenju i faktoru opterećenja za sve razine (elektroprivrede, entiteti i država).

U tablicama 1 i 2 prikazana je potrošnja električne energije, vršno opterećenje i faktor opterećenja za tri scenarija potrošnje za pojedine elektroprivrede i entitete. U svim scenarijima pretpostavljeno je da se područje Distrikta Brčko do kraja planskog razdoblja opskrbljuje od strane EP RS (stoga potrošnja EP RS obuhvaća potrošnju Republike Srpske i Distrikta Brčko).

2 ESTIMATED ELECTRICITY CONSUMPTION

In accordance with the best practice (the application of the MAED model) an estimate for all energy forms has been made, including electricity, separately for each electric utility company and each entity, and finally for Bosnia and Herzegovina as a whole. The following tables contain data on electricity consumption, peak load and load factor for all levels (electric utility companies, entities, and the state).

Tables 1 and 2 show electricity consumption, peak load and load factor for three consumption scenarios for individual electric utility companies and entities. All scenarios assume that the Brčko District area is supplied by the EP RS until the end of the planning period (therefore, the EP RS consumption encompasses the consumption of the Republic of Srpska and the Brčko District).

Tablica 1 – Ukupna potrošnja električne energije, vršno opterećenje sustava i faktor opterećenja sustava u Bosni i Hercegovini i Federaciji BiH
Table 1 – Total electricity consumption, peak system load and system load factor in Bosnia and Herzegovina and the Federation of Bosnia and Herzegovina (BiH)

	BiH			Federacija BiH / Federation of BiH		
Godina / Year	Energija / Energy, GWh	Snaga / Power, MW	Faktor opterećenja / Load factor,%	Energija / Energy, GWh	Snaga / Power, MW	Faktor opterećenja / Load factor,%
2009.	12 733	2 192	66,3	8 746	1 458	68,5
2010.	13 112	2 235	67,0	9 051	1 496	69,1
2011.	13 550	2 311	66,9	9 333	1 544	69,0
2012.	14 004	2 390	66,9	9 624	1 593	69,0
2013.	14 474	2 471	66,9	9 926	1 644	68,9
2014.	14 962	2 556	66,8	10 238	1 697	68,9
2015.	15 468	2 590	68,2	10 561	1 719	70,2
2016.	15 918	2 667	68,1	10 846	1 766	70,1
2017.	16 384	2 747	68,1	11 141	1 816	70,0
2018.	16 866	2 830	68,0	11 447	1 867	70,0
2019.	17 364	2 915	68,0	11 762	1 920	69,9
2020.	17 880	3 003	68,0	12 089	1 975	69,9

Tablica 2 – Ukupna potrošnja električne energije, vršno opterećenje sustava i faktor opterećenja sustava za pojedinu elektroprivredu
Table 2 – Total electricity consumption, peak system load and system load factor per electric utility company

	EP BiH			EP HZHB			EP RS*		
Godina / Year	Energija / Energy, GWh	Snaga / Power, MW	Faktor opterećenja / Load factor, %	Energija / Energy, GWh	Snaga / Power, MW	Faktor opterećenja / Load factor, %	Energija / Energy, GWh	Snaga / Power, MW	Faktor opterećenja / Load factor, %
2009.	5037	898	64,0	3709	565	75,0	3987	795	57,3
2010.	5275	926	65,0	3776	575	75,0	4061	796	58,3
2011.	5485	963	65,0	3848	586	75,0	4217	826	58,3
2012.	5703	1002	65,0	3921	597	75,0	4379	857	58,3
2013.	5930	1041	65,0	3996	608	75,0	4548	890	58,3
2014.	6166	1083	65,0	4072	620	75,0	4724	924	58,4
2015.	6412	1092	67,0	4150	632	75,0	4907	929	60,3
2016.	6659	1135	67,0	4187	637	75,0	5072	960	60,3
2017.	6916	1178	67,0	4225	643	75,0	5243	992	60,3
2018.	7183	1224	67,0	4264	649	75,0	5419	1025	60,3
2019.	7460	1271	67,0	4302	655	75,0	5602	1060	60,4
2020.	7748	1320	67,0	4341	661	75,0	5791	1095	60,4

*EP RS opskrbljuje i područje Distrikta Brčko, pa je uključena i potrošnja Brčkog / EP RS also supplies the Brčko District, so its consumption was also included

3 POSTOJEĆE ELEKTRANE I IZLASCI IZ POGONA

U nastavku je dan sažeti pregled postojećih elektrana na području BiH.

3.1 Federacija BiH

U tablici 3. prikazani su osnovni podaci o postojećim hidroelektranama na području Federacije BiH (FBiH). Ukupna raspoloživa snaga hidroelektrana u FBiH je 1 256 MW s očekivanom godišnjom proizvodnjom 3 149 GWh. U sastavu EP BiH nalaze se tri velike hidroelektrane i nekoliko malih hidroenergetskih objekata ukupne snage 509 MW i očekivane godišnje proizvodnje 1 580 GWh. Na području EP HZHB nalazi se ukupno šest hidroelektrana ukupne snage 747 MW i očekivane godišnje proizvodnje 1 569 GWh.

3 EXISTING POWER PLANTS AND END OF OPERATIONS

A concise review of the existing power plants in Bosnia and Herzegovina follows.

3.1 Federation of Bosnia and Herzegovina

Table 3 shows the basic data on existing hydroelectric power plants on the territory of the Federation of Bosnia and Herzegovina (FBiH). The total available power of hydroelectric power plants in the Federation of Bosnia and Herzegovina is 1 256 MW with the expected yearly production of 3 149 GWh. EP BiH has three large hydroelectric power plants and several smaller hydropower facilities with the total capacity of 509 MW, and the expected yearly production of 1 580 GWh. EP HZHB territory contains a total of six hydroelectric power plants with the total capacity of 747 MW and the expected yearly production of 1 569 GWh.

Tablica 3 – Postojeće hidroelektrane na području Federacije BiH
Table 3 – Existing hydroelectric power plants on the territory of the Federation of BiH

FBiH – postojeće hidroelektrane / existing power plants			
EP BiH			
Naziv / Name	Snaga na pragu / Net capacity, MW	Očekivana godišnja proizvodnja / Expected yearly production, GWh	Korisni sadržaj akumulacije / Useful reservoir content, GWh
Jablanica	175	771	70
Grabovica	114	334	0,4
Salakovac	207	410	1,7
Male HE EP BiH / Small HE EP BiH	13	65	0
Ukupno / Total EP BiH	509	1 580	72,1

EP HZHB			
Čapljina	400	200	3,4
Rama	159,4	650	303,0
Mostar	71,6	247	0,4
Jajce I	58	233	0,5
Jajce II	28	157	0,2
Peć Mlini	30	82	0,2
Ukupno / Total EP HZHB	747	1 569	307,7
Ukupno / Total FBiH	1 256	3 149	379,8

U tablici 4 prikazani su osnovni podaci o termoelektranama na području Federacije BiH. Sve termoelektrane su u sastavu EP BiH, tj. na području EP HZHB postoje samo hidroelektrane. Ukupna snaga termoelektrana na pragu je 1 015 MW. Sve elektrane kao gorivo koriste domaći ugljen (mrki i/ili lignit). Navedene cijene goriva odnose se na ostvarene nabavne cijene goriva u 2006. godini. Pri tome treba uzeti u obzir da su cijene ugljena za termoelektrane u Federaciji BiH regulirane od strane Vlade FBiH [1]. Do 2020. godine iz pogona izlaze jedinice Tuzla G3 (2013. godine), Tuzla G4 (2018. godine) i Kakanj G5 (2018. godine). Kakanj G7 je revitaliziran tijekom 2005. godine. Revitalizacija jedinice Tuzla G5 je završena 2008. godine, a predviđena je i revitalizacija blokova Tuzla G6 i Kakanj G6. Nakon revitalizacije očekuje se da će navedene jedinice izaći iz pogona nakon 2020. godine, tj. nakon kraja promatranog planskog razdoblja. Očekivano produljenje radnog vijeka revitaliziranih jedinica je 15 godina.

Table 4 shows the basic data on thermal power plants on the territory of the Federation of Bosnia and Herzegovina. All the thermal power plants belong to EP BiH, i.e. only hydroelectric power plants exist on the EP HZHB territory. The total available net capacity for thermal power plants is 1 015 MW. All power plants use domestic coal (brown coal and/or lignite) as fuel. The mentioned fuel prices relate to the realised procurement fuel prices in 2006. It should be taken into consideration that the coal prices for thermal power plants in the Federation of Bosnia and Herzegovina are regulated by the Federation of Bosnia and Herzegovina Government [1]. By 2020, the facilities of Tuzla G3 (in 2013), Tuzla G4 (in 2018) and Kakanj G5 (in 2018) will end their operations. Kakanj G7 was revitalised in 2005. Revitalisation of Tuzla G5 was finished in 2008, and the revitalisation of the blocks of Tuzla G6 and Kakanj G6 is planned. Following the revitalisation, it is expected for the said units to end their operations after 2020, i.e. after the end of the monitored planning period. The expected extension of the operation span of revitalised units is 15 years.

Tablica 4 – Postojeće termoelektrane na području Federacije BiH
Table 4 – Existing thermal power plants on the territory of the Federation of BiH

Naziv jedinice / Unit name	Snaga na pragu / Net capacity, MW	Ugljen / Coal	Ogrjevna vrijednost goriva / Heat value of fuel, kJ/kg	Cijena goriva / Fuel price, EUR/GJ	Specifični potrošak topline / Heat rate, kJ/kWh	Izlazak iz pogona / Retirement, Godina / Year
Tuzla G3	85	lignit/mrki / lignite/brown coal	10407	2,27	14404	2013.
Tuzla G4	175	lignit/mrki / lignite/brown coal	9948	2,27	12150	2018.
Tuzla G5	180	lignit/mrki / lignite/brown coal	10430	2,27	12200	iza/after 2020.
Tuzla G6	190	mrki / brown coal	16062	2,27	11810	iza/after 2020.
Kakanj G5	95	mrki / brown coal	13732	2,01	11700	2018.
Kakanj G6	85	mrki / brown coal	11700	2,01	14433	iza/after 2020.
Kakanj G7	205	mrki / brown coal	11400	1,98	12260	iza/after 2020.
Ukupno / Total FBiH/EP BiH	1015	–	–	–	–	–

U pogledu izlazaka iz pogona i revitalizacije važno je istaknuti da proizvodne jedinice Tuzla G3 i Tuzla G4 proizvode i toplinsku energiju kojom se opskrbljuju industrija i kućanstva na području Tuzle. Zbog toga je potrebno na ovim lokacijama planirati zamjenski proizvodni objekt. Slično stanje je i na lokaciji u Kaknju gdje postojeći blokovi opskrbljuju i toplinski konzum. Postoje i ideje o opsrkbi Sarajeva toplinom iz TE Kakanj.

3.2 Republika Srpska

U tablici 5 prikazani su osnovni podaci o postojećim hidroelektranama u Republici Srpskoj. Pri tome treba uzeti u obzir da se HE Dubrovnik I nalazi u hrvatskom elektroenergetskom sustavu i da se proizvodnja ove elektrane dijeli u omjeru 50:50 između Elektroprivrede RS i Hrvatske elektroprivrede (jedan agregat je povezan na sustav EP RS, a drugi na sustav HEP-a). U skladu s tim u tablici 5 prikazani su podaci o snazi i očekivanoj godišnjoj proizvodnji HE Dubrovnik koji se odnose na dio koji koristi EP RS, tj. pola snage (jedan od ukupno dva agregata) i pola proizvodnje (proizvodnja jednog agregata). Ukupna raspoloživa snaga hidroelektrana u RS je 735 MW uz očekivanu godišnju proizvodnju od 2 661 GWh.

As regards the ends of operations and revitalisation it is important to point out that the production units Tuzla G3 and Tuzla G4 also produce thermal energy which supplies the industry and households in the Tuzla area. Therefore it is necessary to plan an alternative production facility at these locations. The condition is similar at the Kakanj location, where the existing blocks also supply thermal consumption. Furthermore, there are also plans for the thermal supply of Sarajevo from the Kakanj thermal power plant (Kakanj TPP).

3.2 The Republic of Srpska (RS)

Table 5 shows the basic data on existing hydroelectric power plants in the Republic of Srpska. It should be taken into consideration that the Hydroelectric Power Plant Dubrovnik (HE Dubrovnik) I is in the Croatian electric power system, and that the power plant's production is shared in a 50:50 ratio between the Power Utility RS, and Hrvatska elektroprivreda (HEP) (one generator is connected to the EP RS system, and the other to the HEP system). In accordance with that, table 5 shows data on power and the expected yearly production of HPP Dubrovnik which apply to the share used by ERS, i.e. half of total power (one of two generators in total) and half of total production (single generator production). Total available capacity of hydroelectric power plants in the Republic of Srpska is 735 MW with the expected yearly production of 2 661 GWh.

Tablica 5 – Postojeće hidroelektrane na području Republike Srpske
Table 5 – Existing hydroelectric power plants on the territory of the Republic of Srpska

Republika Srpska – postojeće hidroelektrane / The Republic of Srpska – existing hydroelectric power plants			
Naziv / Name	Snaga na pragu / Net capacity, MW	Očekivana godišnja proizvodnja / Expected yearly production, GWh	Korisna veličina akumulacije / Useful reservoir size, GWh
HE Višegrad	315	1038	11,0
HE Bočac	110	307,5	5,5
HE Trebinje I	180	535,4	vidi tekst ispod / see text below
HE Trebinje II	7,6	12,5	0,4
HE Dubrovnik (50 %)*	108	695,6	vidi tekst ispod / see text below
Male i industrijske elektrane / Small and industrial power plants	15,2	72,0	0
Ukupno / Total	735,8	2 660,9	274,7

* – HE Dubrovnik I nalazi se na teritoriju RH. Elektroprivreda RS i Hrvatska elektroprivreda d.dijele proizvodnju iz HE Dubrovnik I u omjeru 50 : 50. / HE Dubrovnik I is on the territory of the Republic of Croatia. The Power Utility of the Republic of Srpska and Hrvatska elektroprivreda d.d. share the HE Dubrovnik I production in the ratio 50 : 50.

Korisni sadržaj akumulacije Trebinje je 9,36 GWh sa stanovišta proizvodnje u HE Dubrovnik. Korisna veličina akumulacije Bileća je 1 010 GWh sa sta-

From the viewpoint of HPP Dubrovnik, the useful content of the Trebinje reservoir is 9,36 GWh. From the total production viewpoint of HPP Trebinje I and novišta ukupne proizvodnje u HE Trebinje I i HE Dubrovnik, a korisni sadržaj akumulacije Bileća je 200 GWh sa stanovišta proizvodnje u HE Trebinje I.

Podaci o malim i industrijskim elektranama prikupljeni su od strane EP RS. Osim navedenih na području RS postoji još malih i/ili industrijskih elektrana o kojima podaci nisu poznati.

U tablici 6 prikazani su osnovni podaci o postojećim termoelektranama na području Republike Srpske. Navedenim termoelektranama upravlja EP RS. Raspoloživa snaga ovih termoelektrana iznosi 530 MW. Pri tome treba imati u vidu da je projektirana snaga na pragu TE Ugljevik 280 MW, ali je zbog tehničkih problema moguće postići tek 250 MW. Za postizanje projektirane snage potrebna je rekonstrukcija kotla. TE Gacko i TE Ugljevik predviđene su za revitalizaciju čime će se produljiti životni vijek i ispuniti ekološke norme u pogledu emisije onečišćujućih tvari (čestice, sumpor, NO_x). Očekivana godina izlaska iz pogona revitaliziranih jedinica je nakon 2020. godine.

HPP Dubrovnik, the useful size of the Bileća reservoir is 1 010 GWh, and from the production viewpoint of HPP Trebinje I its useful volume is 200 GWh.

The data on small and industrial power plants was gathered by the ERS. Besides the previously mentioned, there are other small and/or industrial power plants on the territory of the Republic of Srpska, but their data are unknown.

Table 6 shows the basic data on existing thermal power plants on the territory of the Republic of Srpska. The mentioned thermal power plants are under the control of EP RS. The available power of these thermal power plants is 530 MW. However, it should be taken into account that the projected power available at threshold of TPP Ugljevik is 280 MW, but due to technical problems it is possible to achieve only 250 MW. To achieve the projected power, a reconstruction of the boiler is necessary. TPP Gacko and TPP Ugljevik have been scheduled for revitalisation, which will prolong their lifespan and fulfil the environmental standards in view of pollutant substances emissions (particles, sulphur, NO_x). The expected year for the end of operations of the revitalised units is after 2020.

Tablica 6 – Postojeće termoelektrane na području Republike Srpske
Table 6 – Existing thermal power plants on the territory of the Republic of Srpska

Naziv jedinice / Unit name	Snaga na pragu elektrane / Plant net capacity, MW	Vrsta goriva (ugljen) / Fuel type (coal)	Ogrjevna vrijednost goriva / Heat value of fuel, kJ/kg a)	Cijena goriva / Fuel price, EUR/GJ	Specifični potrošak topline / Heat rate, kJ/kWh	Izlazak iz pogona / Retirenment, Godina / Year
Gacko 1	255*	lignit / lignite	8 000	1,45	11 520	iza / after 2017.
Ugljevik 1	235,6	mrki / brown coal	10 200	1,62	11 470	iza / after 2020.
Ukupno / Total ERS	490,6	–	–	–	–	–

* - nominalna snaga na pragu elektrane je 276 MW , a raspoloživa (prije revitalizacije) je 255 MW / nominal power at threshold of the power plant is 276 MW, and available power (before revitalisation) is 255 MW

a) – donja ogrjevna vrijednost / lower heating value

4 ELEKTRANE - KANDIDATI ZA IZGRADNJU

U nastavku je dan sažeti pregled elektrana kandidata na području BiH. S obzirom na relativno veliki ukupni broj kandidata, ovdje se navode podaci za one elektrane čiji se podaci temelje na prethodnim aktivnostima na pojedinom projektu i noveliranim studijama (pred)izvodljivosti i mogućnostima iskorištenja pojedinih vodotoka ili ugljenokopa. Za pojedine termoelektrane, za koje nisu bili poznati podaci o investicijama, ali su uključene u razmatranje, napravljena je procjena usporedbom s podacima o generičkim elektranama kandidatima iz GIS studije [2] i s drugim izvorima o očekivanim visinama investicija u proizvodne objekte.

4 POWER PLANT CANDIDATES FOR CONSTRUCTION

A concise review of candidate power plants in Bosnia and Herzegovina follows. Considering the relatively large total number of candidates, the data given here are only for those power plants whose data are based on previous activities in a certain project, detailed studies of (pre)feasibility and possibilities of exploitation of certain watercourses or coal mines. For certain thermal power plants which investment data was not known, but which have been included in the observation, an assessment has been made comparing the data on generic power plant candidates from the GIS study [2] and from other sources on expected investments in production facilities.

Što se tiče hidroelektrana kandidata za izgradnju postoji nekoliko tzv. zajedničkih objekata koji svojim radom utječu na vodotoke u susjednim državama ili entitetu. Ovi objekti su navedeni u nastavku, ali nisu razmatrani kao ozbiljni kandidati s obzirom na njihov neriješeni i nepoznati položaj koji je potrebno riješiti u izravnim pregovorima i dogovorima zainteresiranih strana.

4.1 Federacija BiH

U tablici 7 prikazani su osnovni podaci o hidroelektranama kandidatima na području Federacije BiH. Prikazana je prosječna moguća neto proizvodnja električne energije, tj. proizvodnja električne energije na pragu elektrane.

Na području EP BiH promatrano je ukupno deset (10) projekata – kandidata za izgradnju. Pri tome su sve male HE promatrane kao jedan projekt. Ukupna snaga kandidata iznosi 732,1 MW s očekivanom godišnjom proizvodnjom od 2 232,2 GWh. Najranija godina ulaska u pogon, za projekt malih HE koji EP BiH izvodi u suradnji s tvrtkom Turboinštitut iz Slovenije je 2009. godina (snaga malih HE u ovom projektu je oko 34 MW, a očekivana proizvodnja 126 GWh). Za ostale projekte pretpostavljeno je da mogu ulaziti u pogon od 2012. godine nadalje. Pri tome treba napomenuti da se radi o optimističnim varijantama najranijeg mogućeg ulaska u pogon s obzirom na stanje aktivnosti na pojedinim projektima.

Na području EP HZHB promatra se ukupno deset (10) kandidata. Pri tome treba imati u vidu da je HE Mostarsko Blato objekt u izgradnji. U svim scenarijima pretpostavljeno je da ova elektrana fiksno ulazi u pogon u 2010. godini. Za projekte malih HE na području EP HZHB pretpostavljeno je da su grupirani po slivovima te se promatraju ukupno tri projekta malih HE. Ukupna snaga svih razmatranih hidroelektrana kandidata iznosi 255 MW s očekivanom godišnjom proizvodnjom 677 GWh. Kao i u slučaju EP BiH i ovdje vrijedi komentar da su prikazane najranije godine ulaska u pogon optimistične.

U tablici 7 prikazani su i objekti koje planira izgraditi tvrtka Intrade Energija d.d. iz Sarajeva te ukupna očekivana snaga malih hidroelektrana na području Federacije BiH.

Ukupno na području Federacije BiH za realizaciju do 2020. godine konkuriraju hidroenergetski projekti snage 1 824,2 MW i očekivane godišnje proizvodnje 4 674,7 GWh. Među kandidatima je i crpna hidroelektrana PHE Bjelimići instalirane snage 2x300 MW s očekivanom godišnjom proizvodnjom 1 029 GWh, ali i potrošnjom od 1 388 GWh u crpnom načinu rada (tj. ova elektrana se u sustavu javlja kao neto potrošač električne energije). Opravdanost rada i izgradnje crpne hi-

Concerning hydroelectric power plant construction candidates, there are several so-called joint facilities which, through their operation, influence watercourses in neighbouring countries or entities. These facilities are mentioned below, but are not considered serious candidates because of their unresolved and unknown position which needs to be settled in direct negotiations and agreements between interested parties.

4.1 Federation of Bosnia and Herzegovina (FBiH)

Table 7 shows the basic data on hydroelectric power plant candidates on the territory of the Federation of Bosnia and Herzegovina. The average possible net electricity production, i.e. electricity production available at threshold, is shown.

A total of ten (10) projects – candidates for construction were monitored on the EP BiH territory. Thereat, all small HPPs were monitored as a single project. The total candidate capacity amounts to 732,1 MW with the expected yearly production of 2 232,2 GWh. The earliest possible year for the start of operations is 2009 for the small HPPs project implemented by the EP BiH in cooperation with the company Turboinštitut from Slovenia (the capacity of the small HPPs from this project is approximately 34 MW, and the expected yearly production is 126 GWh). For other projects it is assumed that they can start operations from 2012 onwards. However, it should be noted that these are optimistic variations of the earliest possible start of operations considering the state of activity on certain projects.

A total of ten (10) candidates were monitored on the EP HZHB territory. However, it should be taken into account that HPP Mostarsko Blato is a facility in construction. All scenarios assume that this power plant will permanently start operations in 2010. For the small HPP projects on EP HZHB territory it is assumed that they are grouped by basins and a total of three small HPP projects was monitored. The total capacity of all hydroelectric power plant candidates considered amounts to 255 MW with the expected yearly production of 677 GWh. As with EP BiH, the comment that the earliest possible years for the start of operations are optimistic applies here as well.

Table 7 also shows the facilities planned for construction by the company Intrade Energija d.d. from Sarajevo, and the total expected power of small hydroelectric power plants on the territory of the Federation of Bosnia and Herzegovina.

The total competition for hydropower projects on the territory of the Federation of Bosnia and Herzegovina to be realised by the year 2020 amounts to 1 824,2 MW of capacity, and 4 674,7 GWh of expecdroelektrane može se provesti satnom analizom rada i dijagrama opterećenja u sustavu što traži posebnu analizu. Osim toga na području Bosne i Hercegovine već postoji jedna crpna hidroelektrana (CHE Čapljina, 400 MW), a nekoliko elektrana ovog tipa postoji i u susjednim sustavima (Hrvatska, Srbija). Potreba za crpnim hidroelektranama, tj. općenito elektranama koje mogu ponuditi brzu promjenu snage (regulaciju), može se očekivati s povećanom izgradnjom intermitentnih izvora kao što su npr. vjetroelektrane. Pri tome treba na odgovarajući način organizirati tržište električne energije, tj. organizirati tržište energije uravnoteženja.

Projekti HE Vrletna Kosa i HE Ugar Ušće nalaze se na međuentitetskoj crti te su se Vlade Federacije BiH i RS dogovarale o zajedničkoj izgradnji ovih hidroelektrana.

U tablici 8 prikazani su osnovni podaci o termoelektranama kandidatima na području Federacije BiH. Na području EP BiH razmatrano je sedam (7) lokacija termoelektrana. Pri tome tri kandidata (Tuzla G7, Tuzla G8 i Kakanj B) imaju praktično jednake karakteristike s obzirom da su za ove elektrane bile poznate samo očekivane instalirane snage. Podaci o investicijama, drugim troškovima i specifičnom potrošku topline su pretpostavljeni. Osobiti problem prilikom razmatranja termoelektrana kandidata predstavlja različita razina obrade pojedinih lokacija (postojeće, nove) što bitno utječe na nesigurnost cijene ugljena i specifične investicije na novim lokacijama u odnosu na postojeće lokacije. Ova nesigurnost se procjenjuje na 30 %.

Postojeće lokacije Tuzla i Kakanj imaju određene preduvjete i komparativne prednosti u odnosu na nove lokacije kao što su postojanje infrastrukture, osigurane lokacije u prostornim planovima, postojanje stručnog kadra i dr. Na lokacijama u Tuzli i Kaknju iz postojećih blokova se osigurava i toplinska energija za industriju i kućanstva te je potrebno voditi računa o izlasku postojećih blokova iz pogona i izgradnje zamjenskih proizvodnih kapaciteta.

Na području EP HZHB razmatrana je mogućnost izgradnje TE Kongora.

ted yearly production. The pump-storage hydroelectric power plant PHPP Bjelimići is also among the candidates, with its installed capacity of 2x300 MW and an expected yearly production of 1 029 GWh, but also with the consumption of 1 388 GWh during the pump-feeding operation mode (i.e. this power plant appears in the system as a net consumer of electricity).

The justifiability of operation and construction of a pump-storage hydroelectric power plant can be established by an hourly analysis of operations and a system load diagram, but that is not the subject of this study. Moreover, a pump-storage hydroelectric power plant already exists on the territory of Bosnia and Herzegovina (PSPP Čapljina, 400 MW), and there are several power plants of this type in the neighbouring systems (Croatia, Serbia) as well. The need for pump-storage hydroelectric power plants, that is, for power plants which can offer a quick power change (regulation) in general, can be expected with the increased construction of intermittent sources such as, for example, wind farms. The electricity market, i.e. the balance energy market, needs to be organised accordingly.

The projects of HPP Vrletna Kosa and HPP Ugar Ušće are situated at the inter-entity line, so the governments of the Federation of Bosnia and Herzegovina and the Republic of Srpska have agreed on a joint construction of these hydroelectric power plants.

Table 8 shows the basic data on thermal power plant candidates on the territory of the Federation of Bosnia and Herzegovina. Seven (7) thermal power plant locations were considered on the EP BiH territory. Three of the candidates (Tuzla G7, Tuzla G8 and Kakanj B) have virtually identical characteristics since only the expected installed powers were known for these power plants. Data on investments, other expenses and specific heat consumption are assumed. Varying levels of analysis for individual locations (existing, new) are a particular problem in considering thermal power plant candidates, which significantly influences the uncertainty of coal prices and specific investments on new locations in relation to existing locations. The uncertainty is estimated at 30 %.

The existing locations Tuzla and Kakanj have certain preconditions and comparative advantages to new locations, such as the existence of infrastructure, locations secured in physical plans, the existence of expert personnel etc. On Tuzla and Kakanj locations, the existing blocks also ensure thermal energy for industry and households so it is necessary to consider the end of operations of existing blocks and the construction of alternative production capacities.

The possibility for the construction of TPP Kongora has been considered on EP HZHB territory.

Tablica 7 – Hidroelektrane kandidati na području Federacije BiH
Table 7 – Candidate hydroelectric power plants on the territory of the Federation of Bosnia and Herzegovina

Federacija BiH / The Federation of BiH					
EP BiH					
Naziv / Name	Snaga na pragu / Net capacity, MW	Očekivana proizvodnja / Expected production, GWh/god. / GWh/y.	Korisna veličina akumulacije / Useful reservoir size, GWh	Specifična investicija / Specific investment, EUR/kW	Trajanje izgradnje / Duration of construction, Godina / Year
Male HE EP BiH / Small HE EP BiH	~100	~380	0,0	1 493	2
Unac	71	250	29,3	963	3
Ustikolina	59	255	0,1	1 396	4
Vranduk	22	103,2	0,0	2 111	4
Glavatičevo[a])	171,8	295	48,3	1 048	5
Vrhpolje	68	157,4	9,8	1 562	4
Čaplje	7,7	56,8	0,1	2 845	4
Goražde	60	234	0,35	1 500	5
Ključ	49	211	-	1 714	4
Konjic[b])	121	290	12,1	1 074	5
Ukupno EP BiH / Total EP BiH	732,1	2 232,2			
EP HZHB					
Mostarsko Blato[c])	60	167	0,4	1 200	4
CHE Vrilo	52	92	16,3	1 149	5
CHE Kablić	52	73	20,6	1 437	5
Han Skela	8,5	36	0,7	1 500	5
Vrletna Kosa	25	63	34,7	1 500	5
Jajce II-proširenje (HE Ugar Ušće) / Jajce II-expansion (HE Ugar Ušće)	15	60	0,3	1 500	5
Male HE HZHB – Sliv T-M-T / Small HE HZHB – T-M-T basin	19,9	127,7	0,0	1 881	2
Male HE HZHB – Sliv Lištice / Small HE HZHB – Lištica basin	7	27,7	0,0	1 832	2
Male HE HZHB – Sliv Gornje Cetine / Small HE HZHB – Upper Cetina basin	12,7	30,7	0,0	1 650	2
Ukupno EP HZHB / Total EP HZHB	252,1	677,1			
Intrade Energija d.o.o., Sarajevo					
PHE Bjelimići[d])	600,0 (–600,0)	1 029 (–1 388)	–	388**	4
Bjelimići	100,0	306,4	0,0	1 660	5
Ukupno Intrade Energija / Total Intrade Energy	700,00	1 335,4 (–1 388)			
Male HE u Federaciji BiH s izdanom koncesijom / Small HE in Federation BiH with granted concession					
Male HE FBiH[e]) / Small HE FBiH[e])	140	430	–	2 000	2
Ukupno FBiH / Total FBiH	1 824,2	4 674,7 (-1 388)			

a) – postoje različiti podaci o ovom projektu; snaga ovisi i rješenju gornjeg djela sliva, projekt nesiguran / data for this project varies, power also depends on the resolution of the upper basin parts, project uncertain,
b) - projekt upitan s ekološkog stanovišta / project environmentally questionable,
c) - HE Mostarsko Blato u izgradnji. Očekivani ulazak u pogon 2010. godine / HE Mostarsko Blato in construction. Expected start of operations in 2010,
d) – crpna hidroelektrana, bez troškova priključka na mrežu / pump-fed hydroelectric power plant, without network connection costs,
e) – procjena, podaci nisu bili dostavljeni / estimate, data were not delivered.

Tablica 8 – Termoelektrane kandidati na području Federacije BiH
Table 8 – Candidate thermal power plants on the territory of the Federation of BiH

EP BiH					
Naziv jedinice / Unit name	Maksimalna snaga / Maximum power, MW	Vrsta goriva (ugljen) / Fuel type (coal)	Specifični potrošak topline / Heat rate, kJ/kWh	Ogrjevna vrijednost goriva / Heat value of fuel, kJ/kg	Cijena goriva / Fuel price, EUR/GJ
Bugojno 1	350 (320)*	lignit / lignite	10 239	10 600	1,48
Tuzla G7	450 (411)	lignit / lignite	8 511	9 500	2,30
Kakanj G8	250 (230)	mrki / brown coal	9 000	13 600	2,30
Kakanj B	450 (411)	mrki / brown coal	8 511	13 600	2,30
Tuzla B G1	500 (465)**	mrki / brown coal	10 680	10 880	2,30
Kamengrad G1	215 (195)*	mrki / brown coal	9 000	11 700	2,30
Tuzla G8	450 (411)	lignit / lignite	8 511	9 500	2,30
EP HZHB					
Kongora	275 (265)*	lignit / lignite	9 300	7 380	1,53

* – moguća su dva bloka na lokacijama / two blocks are possible at the locations
** – moguća su tri bloka na lokaciji / three blocks are possible at the location

Na području EP HZHB istražen je ili je u fazi istraživanja određeni broj lokacija za vjetroelektrane. S obzirom na specifičnost konfiguracije pojedine vjetroelektrane (veći broj vjetroagregata povezanih u jednu vjetroelektranu), razmatrana je generička vjetroelektrana instalirane snage 50 MW.

A certain number of potential wind farm locations were researched or are being researched on EP HZHB territory. Considering the specific configuration of a single wind farm (a large number of wind powered generators connected into one wind farm), a generic wind farm with 50 MW of installed capacity was considered.

4.2 Republika Srpska

U tablici 9 prikazani su osnovni podaci o hidroelektranama kandidatima na području Republike Srpske. Razmatra se ukupno petnaest (15) projekata ukupne snage 1 167,6 MW i očekivane godišnje proizvodnje 2 945 GWh. Projekti malih HE modelirani su u nekoliko grupa ukupne snage 281,7 MW.

HE Dubrovnik 2 je projekt koji zajednički planiraju EP RS i HEP d.d. (Hrvatska). U tablici je prikazan dio koji bi pripadao EP RS (50 %).

HE Ugar Ušće je zajednički projekt s Federacijom BiH (ukupno planirana snaga je 40 MW, podjela potencijala 50 % : 50 %).

Osim objekata navedenih u tablici 9 u planu je i hidroelektrana na donjoj Sutjesci u sklopu projekta Donja Drina, ali još nije definirano tehničko rješenje.

Hidroelektrane Dabar, Nevesinje i Bileća pripadaju projektu Gornji Horizonti koji je u izgradnji. Do sada je u projekt uloženo oko $80 \cdot 10^6$ EUR (mjerenja, ispitivanja, elaborati, studije, projekti, prikupljanje suglasnosti, izgradnja tunela Fatničko polje – akumulacija Bileća, izgradnja tunela Dabarsko polje – Fatničko polje i drugo). Izgradnjom sustava Gornji Horizonti povećava se

4.2 The Republic of Srpska

Table 9 shows the basic data on hydroelectric power plant candidates on the territory of the Republic of Srpska. Fifteen (15) projects of 1 167,6 MW of total capacity and expected yearly production of 2 945 GWh are considered. The small HPP projects are modelled in several groups with the total power of 281,7 MW.

HPP Dubrovnik 2 is a project jointly planned by EP RS and HEP d.d. (Croatia). The table shows the share which would belong to EP RS (50 %).

HE Ugar Ušće is a joint project with the Federation of Bosnia and Herzegovina (total planned capacity is 40 MW, the share ratio of potentials is 50 % : 50 %).

Besides the facilities listed in table 9, a hydroelectric power plant is also planned on Lower Sutjeska within the Lower Drina project, but a technical solution has still not been defined.

Hydroelectric power plants of Dabar, Nevesinje and Bileća belong to the Upper Horizons project which is in construction. So far, approximately $80 \cdot 10^6$ EUR has been invested in the project (measurements, tests, surveys, studies, projects, obtaining consent, construction of the Fatnik field tunnel – Bileća reservoir, construction of the Dabar field – Fatnik field tunnel, etc). The construction of the Upper Horizons system proizvodnja električne energije u nizvodnim sustavima.

increases the electricity production in downstream systems.

Tablica 9 – Hidroelektrane kandidati na području Republike Srpske
Table 9 – Candidate hydroelectric power plants on the territory of the Republic of Srpska

Naziv / Name	Maksimalna snaga na pragu / Maximum power at threshold, MW	Očekivana proizvodnja / Expected production, GWh/god. / GWh/y.	Korisna veličina akumulacije / Useful reservoir size, GWh	Specifična investicija / Specific investment, EUR/kW	Trajanje izgradnje / Duration of construction, Godina / Years
Male HE na teritoriju RS / Small HE on RS territory	281,7	740	–	1 750	2
Buk Bijela	132	350	20,0	2 121	4,5
Foča	56	199	0,2	1 512	4
Dabar	160	271	42,7	1 049	4,5
Bileća	36	117	3,9	1 417	3,5
Dubrovnik 2	152	159	6,5	1 153	4
Nevesinje	60	101	54,1	2 027	5
Krupa	49	140	0,3	1 528	5
Banja Luka niska / Banja Luka low	37	187	0,5	2 316	5
Novoselija	16	70	0,1	1 559	2,5
Paunci	42,3	160	–	–	–
Mrsovo	43,8	165	–	–	–
Ulog (Nedavić)	32,8	75	–	–	–
Ugar Ušće – 50%*	20	–	–	–	–
Ključ*	49	211	131,1	2 998	4
Ukupno / Total	1 167,6	2 945			

* – projekti na međuentitetskoj crti razdvajanja / projects on the entity division line

Za izgradnju hidroelektrana na Drini partner EP RS-u je Elektroprivreda Srbije (projekt Gornja Drina koji obuhvaća objekte Buk Bijela, Foča, Paunci i Donja Sutjeska). Ulazak u pogon HE Buk Bijela planiran je do 2015. godine, a ostale elektrane iz projekta očekuju se u pogonu do 2018. godine. Do 2013. godine moguć je ulazak u pogon hidroelektrana Mrsovo i Ulog.

U tablici 10 prikazani su osnovni podaci o termoelektranama kandidatima na području Republike Srpske. Razmatrane su tri lokacije: Stanari, Ugljevik i Gacko.

Na lokaciji Gacko pretpostavljena je mogućnost izgradnje dva bloka (2x330 MW) s najranijim godinama ulaska u pogon 2015. i 2016. Prema dosadašnjim planovima projekt bi zajednički realizirali EP RS i ČEZ (Češka elektroprivredna tvrtka).

Ugljevik 2 je projekt koji EP RS planira graditi u suradnji s američkom tvrtkom AES (udio EP RS 49 %). Za ovaj projekt izrađena je predstudija izvodljivosti. Planirana godina ulaska u pogon je 2014.

For the construction of hydroelectric power plants on Drina, EP RS's partner is the Electric Power Industry of Serbia (the Upper Drina project encompasses the facilities Buk Bijela, Foča, Paunci and Lower Sutjeska). The start of operations for the HPP Buk Bijela is planned for the year 2015, and the other power plants included in the project are expected to start operations by the year 2018. By 2013 it is possible that hydroelectric power plants Mrsovo and Ulog start operations.

Table 10 shows the basic data on thermal power plant candidates on the territory of the Republic of Srpska. Three locations were considered: Stanari, Ugljevik and Gacko.

At the Gacko location, the possibility for the construction of two blocks (2x330 MW) is assumed with the years of the earliest start of operations being 2015 and 2016. According to the plans so far, the project would be jointly realised by EP RS and ČEZ (Czech power utility company).

Ugljevik 2 is a project planned for construction by EP RS in cooperation with the American company AES (EP RS share 49 %). Pre-feasibility study was made for this project. The planned year for the start of operations is 2014.

Tablica 10 – Termoelektrane – kandidati na području Republike Srpske
Table 10 – Thermal power plants – candidates on the territory of Republic of Srpska

Naziv / Name	Maksimalna snaga (na pragu) / Maximum power (net capacity), MW	Vrsta goriva (ugljen) / Fuel type (coal)	Specifični potrošak topline / Heat rate, kJ/kWh	Ogrjevna vrijednost goriva / Heat value of fuel, kJ/kg	Cijena goriva / Fuel price, EUR/GJ	Fiksni troškovi pogona i održavanja / Fixed operating and maintenance costs, EUR/k/W/mjesec / EUR/kW/month
ERS						
Ugljevik 2	400 (380)	mrki / brown coal	9 000	10 200	1,62	3,0
Gacko 2*	330 (300,5)	lignit / lignite	9 000	8 100	1,57	8,8
EFT Grupa / EFT Group						
Stanari	410 (388,7)	lignit / lignite	9 230	9 100	1,32	3,0

* – moguća su dva bloka na lokaciji / two blocks are possible at the location

Na početku 2008. godine položaj projekta TE Stanari je bio takav da je potpisan ugovor o koncesiji za izgradnju s Vladom RS. Prema ovom ugovoru elektrana Stanari je namijenjena za tržište (engl. *Merchant Plant*). Drugim riječima, iako će elektrana biti izgrađena na području BiH moguće je da će sva električna energija iz ove elektrana biti namijenjena stranim tržištima, tj. onome tko ponudi najbolju cijenu. Zbog toga se kod optimizacije izgradnje ova elektrana i njen utjecaj na sustav razmatra na dva načina: elektrana proizvodi za tržište u BiH i elektrana proizvodi isključivo za izvoz. Prema posljednjim informacijama (kolovoz 2009.) pripremni (zemljani) radovi su u tijeku.

In early 2008, the position of the TPP Stanari project was such that a contract for construction concession has been signed with the Government of the Republic of Srpska. According to this contract, the Stanari power plant is a merchant plant. In other words, even though the power plant will be built on the territory of Bosnia and Herzegovina, it is possible that all electricity produced in this power plant will be intended for the foreign markets, i.e. for the highest bidders. That is why this power plant and its influence on the system are considered in two ways concerning construction optimisation: whether the power plant produces for the Bosnia and Herzegovina market, or only for export. According to the latest information (August 2009) the preparatory (ground) work is in progress.

5 ANALIZA UJEDNAČENIH GODIŠNJIH TROŠKOVA – TERMOELEKTRANE

U nastavku je prikazana analiza ujednačenih godišnjih troškova (engl. *Screening Curve Analysis*) za termoelektrane kandidate i termoelektrane predviđene za revitalizaciju na području Bosne i Hercegovine te hidroelektrane i vjetroelektrane.

5.1 Troškovi termoelektrana

Na slici 1 prikazane su krivulje troškova uz pretpostavljene cijene goriva i investicije. Za objekte na području Federacije BiH za koje nije dobivena cijena ugljena od strane elektroprivreda, pretpostavljena je cijena u skladu s odlukom Vlade FBiH o cijenama ugljena za termoelektrane (tj. 2,30 EUR/GJ).

TE Gacko 1 i TE Ugljevik 1 iskazuju znatno veće stalne i promjenljive troškova pogona i održavanja u odnosu na ostale elektrane u sustavu, što

5 SCREENING CURVE ANALYSIS – THERMAL POWER PLANTS

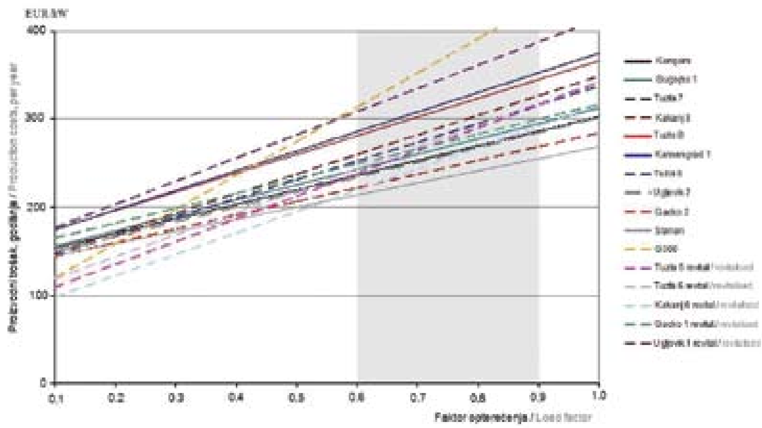
This chapter elaborates on the screening curve analysis for thermal power plant candidates, thermal power plants scheduled for revitalisation on Bosnia and Herzegovina territory, hydroelectric power plants and wind farms.

5.1 Thermal power plants costs

Figure 1 shows the screening curves with assumed fuel prices and investments. For facilities on the territory of the Federation of Bosnia and Herzegovina for which the electric utility companies did not disclose coal prices, the prices were assumed in accordance with the decision of the Government of the Federation of Bosnia and Herzegovina on coal prices for thermal power plants (i.e. 2,30 EUR/GJ).

TPP Gacko 1 and TPP Ugljevik 1 show significantly larger constant and variable operations and maintenance costs in relation to other power plants in the system, bitno utječe na isplativost revitalizacije ovih postrojenja, osobito TE Ugljevik 1. Uz navedene pretpostavke o cijenama ugljena od elektrana kandidata osobito su interesantni projekti TE Stanari i TE Gacko 2. Kao najmanje atraktivna investicija pokazuje se plinska elektrana, zbog visoke cijene plina u odnosu na domaći ugljen. Treba istaknuti da analiza pomoću krivulja troškova ima ograničeni domet u smislu sagledavanja uklapanja pojedine proizvodne jedinice u promatrani elektroenergetski sustav [3] i služi kao okvirna procjena za sužavanje izbora ukupnog broja kandidata.

which significantly influences the cost effectiveness of the revitalisation of these plants, especially of TPP Ugljevik 1. With the given coal price assumptions, the projects TPP Stanari and TPP Gacko 2 are of special interest among power plant candidates. The least attractive investment is a gas power plant, because of high gas prices in comparison with domestic coal. It should be pointed out that the screening analysis has a limited range in the sense of observing the integration of an individual production unit in the monitored electric power system [3], and serves as an approximation for the narrowing down of choices from the total number of candidates.



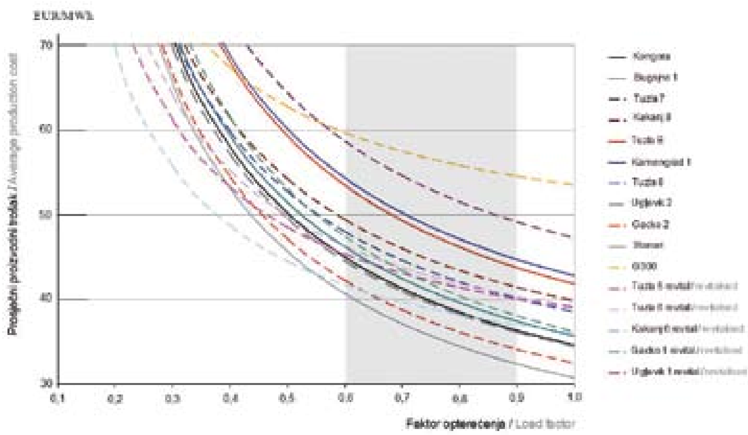
Slika 1 — Krivulje troškova za termoelektrane kandidate i revitalizacije
Figure 1 — Screening curves for thermal power plant candidates and revitalisations

U tablici 11 i na slici 2 prikazani su podaci o prosječnom proizvodnom trošku pojedine termoelektrane (EUR/MWh) tijekom njenog životnog vijeka ovisno o faktoru opterećenja, tj. broju sati iskorištenja maksimalne snage elektrane. Za faktor opterećenja 0,80 što odgovara 7 000 sati rada godišnje, prosječni proizvodni trošak termoelektrana kandidata na ugljen (dakle bez revitaliziranih jedinica za koje se pretpostavlja da će raditi s manjim brojem sati rada – do 6 000) kreće se u rasponu 34,4 EUR/MWh do 47,1 EUR/MWh.

Table 11 and figure 2 show information on average production costs of an individual power plant (EUR/MWh) during its life span depending on the load factor, i.e. the number of hours the maximum power of the power plant was used. For a 0,80 load factor, which corresponds to 7 000 operation hours per year, the average production cost for a coal-powered thermal power plant candidate (therefore without the revitalised units which will approximately operate with a decreased number of operation hours - up to 6 000 hours) is in the range between 34,4 EUR/MWh and 47,1 EUR/MWh.

Tablica 11 – Prosječni proizvodni trošak elektrana kandidata i revitaliziranih jedinica ovisno o faktoru opterećenja
Table 11 – The average production cost of candidate power plants and revitalised units depending on the load factor

Elektrana / Power plant	Faktor opterećenja / Load factor									
	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
	EUR/MWh									
Kongora	175,2	97,1	71,0	58,0	50,2	45,0	41,3	38,5	36,3	34,6
Bugojno	177,9	98,9	72,5	59,4	51,5	46,2	42,4	39,6	37,4	35,7
Tuzla 7	166,6	95,4	71,7	59,8	52,7	48,0	44,6	42,1	40,1	38,5
Kakanj 8	169,5	97,5	73,4	61,4	54,2	49,4	46,0	43,4	41,4	39,8
Tuzla B	199,6	111,9	82,7	68,1	59,3	53,5	49,3	46,2	43,7	41,8
Kamengrad	199,1	112,3	83,3	68,8	60,1	54,4	50,2	47,1	44,7	42,8
Tuzla 8	166,6	95,4	71,7	59,8	52,7	48,0	44,6	42,1	40,1	38,5
Ugljevik 2	170,8	95,0	69,8	57,2	49,6	44,5	40,9	38,2	36,1	34,4
Gacko 2	164,6	91,2	66,7	54,5	47,1	42,2	38,7	36,1	34,1	32,4
Stanari	165,4	90,6	65,6	53,1	45,7	40,7	37,1	34,4	32,4	30,7
G300	136,9	90,5	75,1	67,4	62,8	59,7	57,5	55,8	54,5	53,5
Tuzla 5 revital. / Tuzla 5 revitalised	124,7	77,1	61,2	53,3	48,5	45,3	43,1	41,4	40,1	39,0
Tuzla 6 revital. / Tuzla 6 revitalised	135,6	82,0	64,2	55,2	49,9	46,3	43,7	41,8	40,3	39,2
Kakanj 6 revital. / Kakanj 6 revitalised	111,8	69,7	55,7	48,7	44,5	41,7	39,7	38,2	37,0	36,1
Gacko 1 revital. / Gacko 1 revitalised	188,4	103,8	75,6	61,5	53,1	47,4	43,4	40,4	38,0	36,2
Ugljevik 1 revital. / Ugljevik 1 revitalised	201,8	115,9	87,3	73,0	64,4	58,7	54,6	51,5	49,1	47,2



Slika 2 — Prosječni proizvodni trošak elektrana kandidata i revitaliziranih jedinica ovisno o faktoru opterećenja
Figure 2 — The average production cost of candidate power plants and revitalised units depending on the load factor

5.2 Troškovi hidroelektrana i vjetroelektrana

U nastavku (tablica 12 i slika 3) je prikazana analiza pomoću krivulje troškova za projekte hidroelektrana i za tipsku vjetroelektranu VE50. Za izračun prosječnog godišnjeg troška po jedinici snage tj. za prosječnu proizvodnu cijenu pretpostavljen je životni vijek za hidroelektrane 50 godina, a za vjetroelektrane 20 godina. Za tipsku vjetroelektranu VE50 prikazane su varijante NISKA (specifična investicija 1 000 EUR/kW, faktor opterećenja 0,34) i VISOKA (specifična investicija 1 500 EUR/kW, faktor opterećenja 0,25).

5.2 Costs of hydroelectric power plants and wind farms

The screening analysis for hydroelectric power plant projects and the typal wind farm VE50 follows (table 12 and figure 3). For the calculations of the average yearly cost per power unit, i.e. for the average production price, the assumed lifespan for hydroelectric power plants is 50 years, and 20 years for wind farms. For the typal wind farm VE50 the versions shown are LOW (specific investment 1 000 EUR/kW, load factor 0,34) and HIGH (specific investment 1 500 EUR/kW, load factor 0,25).

Tablica 12 – Godišnji troškovi po jedinici snage i troškovi proizvodnje hidroelektrana i tipske vjetroelektrane kandidata za izgradnju
Table 12 – The yearly cost per power unit and production costs for hydroelectric power plants and the typal wind farm candidate for construction

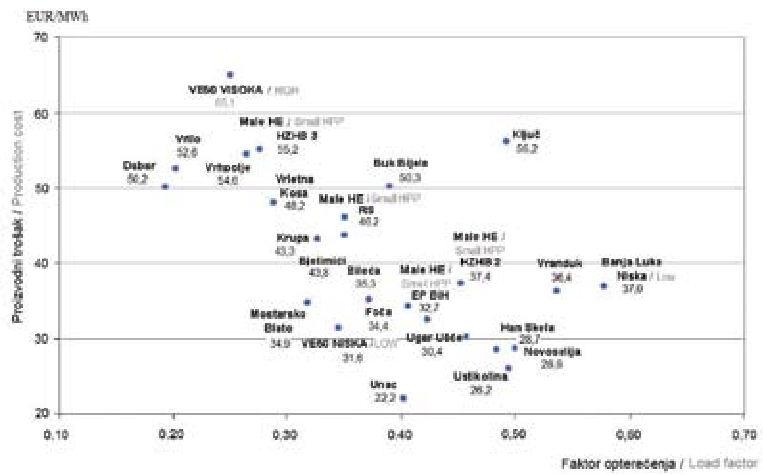
Objekt / Facility	EUR/kW godišnje / per year	Faktor iskoristenja snage / Capacity factor	EUR/MWh
Unac	78,2	0,40	22,2
Male HE HZHB sliv T-M-T / Small HE HZHB T-M-T basin	152,1	0,73	23,7
Ustikolina	113,0	0,49	26,2
Han Skela	121,4	0,48	28,7
Novoselija	126,2	0,50	28,8
Ugar Ušće	121,4	0,46	30,4
Čaplje	229,8	0,84	31,2
Vjetroelektrane NISKA / Wind farms LOW	95,3	0,34	31,6
Male HE EP BiH / Small HE EP BiH	120,9	0,42	32,7
Foča	122,4	0,41	34,4
Mostarsko Blato	97,3	0,32	34,9
Bileća	114,7	0,37	35,3
Vranduk	170,7	0,54	36,4
Banja Luka niska / Banja Luka low	187,2	0,58	37,0
Male HE HZHB sliv Lištice / Small HE HZHB Lištica basin	148,2	0,45	37,4
Krupa	123,7	0,33	43,3
Bjelimići	134,3	0,35	43,8
Male HE ERS / Small HE ERS	141,6	0,35	46,2
Vrletna Kosa	121,4	0,29	48,2
Dabar	85,1	0,19	50,2
Buk Bijela	171,5	0,39	50,3
Vrilo	93,1	0,20	52,6
Vrhpolje	126,4	0,26	54,6
Male HE HZHB sliv Gornje Cetine / Small HE HZHB Upper Cetina basin	133,5	0,28	55,2
Ključ	242,1	0,49	56,2
Vjetroelektrane – VISOKA / Wind farms - HIGH	142,5	0,25	65,1
Kablić	116,4	0,16	82,9
Dubrovnik	93,5	0,12	89,4
Nevesinje	163,9	0,19	97,4

Za hidroelektrane/vjetroelektrane skrining krivulja predstavlja točku na grafičkom prikazu kod koje vertikalna koordinata prikazuje trošak (iskazan u EUR/kW godišnje, tj. ako se prikazuje prosječna proizvodna cijena kao na slici 3 u EUR/MWh), a horizontalna koordinata prikazuje faktor opterećenja za prosječnu godišnju proizvodnju promatrane elektrane.

Osim rangiranja prema prosječnim specifičnim troškovima proizvodnje i prosječnoj proizvodnoj cijeni, za projekte hidroelektrana je važno sagledati najraniju moguću godinu ulaska u pogon i druge moguće probleme u realizaciji projekata (npr. izgradnja tzv. zajedničkih objekata), kao i po-

For hydroelectric power plants / wind farms, the screening curve is a point on the graphic presentation at which the vertical coordinate presents the cost (in EUR/kW per year, i.e. if the average production price is shown as in figure 3 in EUR/MWh), and the horizontal coordinate presents the load factor for the average yearly production of the monitored power plant.

Besides the ranking according to average specific production costs and average production price, for the hydroelectric power plant projects it is important to consider the earliest possible year for the start of operations, other possible problems during project realisation (for example, the construction of the so-



Slika 3 — Prosječna proizvodna cijena tijekom životnog vijeka za hidroelektrane i vjetroelektrane kandidate za izgradnju
Figure 3 — The average production price during the lifespan of a hydroelectric power plant and wind farm candidate for construction.

trebe sustava za energijom i snagom iz hidroelektrana. U tom smislu realne godine ulaska u pogon novih hidroelektrana su od 2014. godine nadalje, osim projekata koji su već u izgradnji (praktično samo male HE i HE Mostarsko Blato).

U pogledu vjetroelektrana stanje je povoljnije što se tiče potrebnog vremena pripreme za izgradnju i izgradnje, ali se problemi mogu očekivati u rokovima isporuke opreme (od narudžbe do isporuke oko 2 godine). Osim toga, tijekom 2007. godine zbog povećane potražnje za vjetroturbinama došlo je do općenitog povećanja razine investicijskog troška za vjetroelektrane (ostvarene narudžbe tijekom 2007. bilježe prosjek od 1 300 EUR/kW). Očekivana cijena vjetroelektrane više nije na razini od 1 000 EUR/kW, već u rasponu od 1 000 EUR/kW do čak 1 500 EUR/kW. U tom smislu je na slici 3 prikazan i utjecaj promjene specifične investicije i očekivanog faktora opterećenja na prosječnu proizvodnju cijenu iz VE.

6 SCENARIJI RAZVOJA EES BIH

Broj mogućih scenarija je vrlo velik. U nastavku su prikazana i komentirana samo dva od njih (S1 i S2), koji daju okvirni pregled mogućih događanja do 2020. godine. Vrlo velik utjecaj na buduća događanja će imati kvaliteta suradnje pojedine elektroprivrede kod izgradnje vlastitih proizvodnih pogona. Isto tako, u mnogome će sve ovisiti o opredjeljenju za podmirivanjem samo vlastite potrošnje ili izvozna orijentacija, kad je električna energija u pitanju. Ova okre-

called joint facilities), and also the system requirements for energy and power from hydroelectric power plants. In that sense, the realistic years for the start of operations of new hydroelectric power plants are from 2014 onwards, except for the projects already in construction (only small HPPs and HPP Mostarsko Blato).

When it comes to wind farms, the condition is more favourable concerning the necessary preparation time for construction and the construction itself, but problems can be expected with deadlines for equipment delivery (from order to delivery, approximately 2 years). Furthermore, during 2007, due to increased demand for wind turbines, there was a general increase in the level of investment costs for wind farms (realised orders during 2007 record an 1 300 EUR/kW average). The expected wind farm price is no longer at the 1 000 EUR/kW level, but in the range from 1 000 EUR/kW up to 1 500 EUR/kW. In that sense, figure 3 also shows the influence of the change of specific investment and the expected load factor on the average wind farm production price.

6 DEVELOPMENT SCENARIOS FOR THE ELECTRIC POWER SECTOR (EPS) OF BIH

There is a very large number of possible scenarios. This chapter elaborates and comments on only two of them (S1 and S2) which give us an approximation of possible events until year 2020. The quality of cooperation an individual electric utility company will give in the process of construction of its production drives will greatly influence future events. Moreover, when electricity is concerned, in many respects everything will depend on the commitment to either the exclusive fulfilment of own consumption or the orientation towards export. The orientation towards export will, of course, be stinutost prema izvozu će, dakako, biti uvjetovana stanjem u ostalim zemljama regije.

pulated by the condition in other countries of the region.

6.1 Scenarij S1

Prema ovom scenariju, sustav BiH je optimiaran kao jedna cjelina, uz kriterij podmirivanja potrošnje na području BiH.

6.1 The S1 scenario

In this scenario, the Bosnia and Herzegovina system is optimised as a whole, with the criterion of meeting the consumption needs on the Bosnia and Herzegovina territory.

Tablica 13 – Raspored ulaska u pogon elektrana za EES BiH za scenarij S1
Table 13 – Start of operations schedule for EPS BiH power plants under scenario S1

Snaga na pragu elektrane / Power plant power at threshold				
Godina / Year	HE / HPP	MW	TE / TPP	MW
2010.	Mostarsko Blato	60		
2013.			Stanari	389
2018.			Tuzla 7	411
2020.			Kakanj 8	230
Ukupno / Total	60		1 030	
Ukupno / Total	1 090			

U pogon ulazi ukupno 1 090 MW, od toga 1 030 MW u termoelektranama. U pogon ulaze TE Stanari (2013., 389 MW na pragu), Tuzla 7 (2018., 411 MW na pragu) i Kakanj (2020., 230 MW). Izgradnja blokova u Tuzli i Kaknju omogućit će i kontinuiranu opskrbu toplinom potrošača na tim područjima s obzirom na izlazak iz pogona postojećih proizvodnih jedinica. U tablici 14 prikazana je struktura proizvodnih kapaciteta i rezerva sustava. Rezerva sustava je u svim godinama veća od 40 %. Udio TE u ukupnoj snazi elektrana u sustavu na kraju razdoblja je 53 %. Nakon kraja planskog razdoblja prvi termoenergetski objekt ulazi u pogon 2022. godine.

A total of 1 090 MW will start operations, 1 030 MW of which in thermal power plants. TPP Stanari (year 2013, 389 MW at threshold), Tuzla 7 (year 2018, 411 MW at threshold) and Kakanj (year 2020, 230 MW) will start operations. The construction of blocks in Tuzla and Kakanj will also enable a continuous heating supply for consumers in those areas, considering the end of operations of existing production units. Table 14 shows the structure of production capacities and the system reserve. The system reserve is higher than 40 % in all the years. The share of thermal power plants in the total power of the system power plants is 53 % at the end of the period. After the end of the planning period, the first thermal power facility will start operations in 2022.

Tablica 14 – Struktura proizvodnih kapaciteta, vršno opterećenje i rezerva u sustavu EES BiH za scenarij S1
Table 14 – The structure of production capacities, peak load and system reserve of EPS BiH for the S1 scenario

Godina / Year	HE postojeće / HPP existing	HE nove / HPP new	TE postojeće / TPP existing	TE nove / TPP new	Ukupno / Total	Vršno opterećenje / Peak load	Rezerva sustava / System reserve
	MW						%
2009.	1 991	0	1 087	0	3 078	2 192	40,4
2010.	1 991	60	1 479	0	3 530	2 235	57,9
2011.	1 991	60	1 329	0	3 380	2 311	46,3
2012.	1 991	60	1 609	0	3 660	2 390	53,2
2013.	1 991	60	1 524	389	3 964	2 471	60,4
2014.	1 991	60	1 524	389	3 964	2 556	55,1
2015.	1 991	60	1 524	389	3 964	2 590	53,0
2016.	1 991	60	1 524	389	3 964	2 667	48,6
2017.	1 991	60	1 524	389	3 964	2 747	44,3
2018.	1 991	60	1 254	800	4 105	2 830	45,1
2019.	1 991	60	1 254	800	4 105	2 915	40,8
2020.	1 991	60	1 254	1 030	4 335	3 003	44,3

U tablici 15 prikazana je bilanca podmirenja potrošnje električne energije u BiH i mogućnost izvoza električne energije. U svakoj godini postoji mogućnost izvoza, uz pretpostavku da postojeće revitalizirane termoelektrane imaju vrijeme iskorištenja maksimalne snage od 6 000 h/god, a nove jedinice 7 000 h/god. U tom slučaju prosječno je moguće izvoziti oko 1 850 GWh/god. Na kraju razdoblja udio termoelektrana u ukupnoj proizvodnji je oko 2/3.

Table 15 shows the balance for settling the electricity consumption in Bosnia and Herzegovina and the possibility for the export of electricity. Every year there is the possibility for export, with the assumption that the existing revitalised thermal power plants have the time utilisation of maximum power of 6 000 h/year, and new units 7 000 h/year. When that is the case, it is on average possible to export approximately 1 850 GWh/year. At the end of the period, the thermal power plant share in total production is approximately 2/3.

Tablica 15 – Bilanca proizvodnje električne energije EES BiH za scenarij S1
Table 15 – The electricity production balance in EPS BiH for the S1 scenario

Godina / Year	HE / HPP	TE / TPP	Uvoz / Import	Ukupno raspoloživo / Available total	Potrošnja / Consumption EES BiH	Mogući izvoz / Possible export
	GWh					
2009.	5 808	6 443	481	12 733	12 733	1 956
2010.	5 975	7 118	19	13 112	13 112	1 757
2011.	5 975	7 425	149	13 550	13 550	2 238
2012.	5 975	8 029	0	14 004	14 004	1 628
2013.	5 975	8 499	0	14 474	14 474	1 175
2014.	5 975	8 987	0	14 962	14 962	3 036
2015.	5 975	9 493	0	15 468	15 468	2 531
2016.	5 975	9 943	0	15 918	15 918	2 087
2017.	5 975	10 409	0	16 384	16 384	1 627
2018.	5 975	10 891	0	16 866	16 866	1 141
2019.	5 975	11 389	0	17 364	17 364	2 723
2020.	5 975	11 905	0	17 880	17 880	2 213

U tablici 16 prikazana je ukupna potrošnja ugljena i emisija CO_2 za slučajeve sa i bez izvoza električne energije (za slučaj izvoza pretpostavljeno je iskorištenje maksimalne snage postojećih/revitaliziranih elektrana od 6 000 h/god).

Table 16 shows the total coal consumption and CO_2 emissions for cases with and without the export of electricity (in the case of export the assumed maximum power use of existing/revitalised power plants is 6 000 h/god).

Tablica 16 – Potrošnja ugljena i emisija CO_2 EES BiH za scenarij S1
Table 16 – EPS BiH coal consumption and CO_2 emissions for the S1 scenario

Godina / Year	Potrošnja ugljena / Coal consumption		Emisija / Emissions CO_2	
	milijuni tona / millions of tonnes		milijuni tona / millions of tonnes	
	Bez izvoza / Without export	S izvozom / With export	Bez izvoza / Without export	S izvozom / With export
2009.	7,51	9,66	7,6	9,8
2010.	8,07	10,13	8,0	10,1
2011.	8,31	9,17	8,5	9,3
2012.	8,81	10,71	8,9	10,8
2013.	8,82	12,51	8,7	12,3
2014.	9,36	12,51	9,2	12,3
2015.	9,91	12,51	9,7	12,3
2016.	10,39	12,51	10,2	12,3
2017.	10,87	12,51	10,7	12,3
2018.	11,00	13,32	10,6	12,9
2019.	11,47	13,32	11,0	12,9
2020.	11,59	14,38	11,4	14,2
Ukupno / Total	124,4	150,8	123,1	149,5

6.2 Scenarij S2

U scenariju S2 precizno je definirana realizacija projekata malih hidroelektrana i vjetroelektrana u skladu s najavama i planovima elektroprivrednih tvrtki i dodijeljenim koncesijama. Ostali projekti promatraju se kao ravnopravni kandidati za izgradnju. Ovaj scenarij može se smatrati izrazito ekološki orijentiranim scenarijem. U tablici 17 prikazan je raspored ulazaka u pogon (fiksirani ulasci te rezultati optimizacije).

6.2 Scenario S2

In the S2 scenario, the realisation of the small hydroelectric power plant and wind farm projects is strictly defined in accordance with the announcements and plans of electric utility companies and granted concessions. Other projects are monitored as equal candidates for construction. This scenario can be considered as an especially environmentally oriented one. Table 17 shows the schedule of starts of operations (fixed starts and optimisation results).

Tablica 17 – Raspored ulazaka u pogon za EES BiH za scenarij S2
Table 17 – Start of operations schedule for EES BiH under scenario S2

	Snaga na pragu elektrane / Plant net capacity				
Godina / Year	HE / HPP	MW	TE / TPP	MW	VE / Wind farms, MW
2009.	Male HE RS / Small HE RS	42			50
2010.	Mostarsko Blato Male HE EP HZHB / Small HE EP HZHB Male HE EP BiH / Small HE EP BiH	114			50
2011.	Male HE EP HZHB / Small HE EP HZHB Male HE RS / Small HE RS	49			50
2012.					50
2013.	Male HE RS / Small HE RS	42			50
2014.			Gacko 2	300	
2015.	Male HE EP HZHB / Small HE EP HZHB Male HE RS / Small HE RS	55			
2017.	Male HE RS / Small HE RS	42			
2018.			Stanari	389	
Ukupno / Total	345		689		250
Ukupno / Total	1 284				

Do 2020. godine u pogon ulazi ukupno 1 284 MW snage na pragu elektrana, od toga 345 MW hidroelektrana (većinom projekti malih HE), 250 MW vjetroelektrana te dvije termoelektrane, Gacko u 2014. godini i Stanari u 2019. godini.

U ukupnoj proizvodnji električne energije udio hidroelektrana s oko 44 % na početku planskog razdoblja opada na 39 % u 2020. godini. Istovremeno udio termoelektrana ostaje približno stalan (promjena s oko 55% na oko 57 %). Ostatak potrebne električne energije osigurava se iz uvoza (koji prestaje nakon 2011. godine) i iz vjetroelektrana čiji udio u ukupnoj proizvodnji u 2020. godini iznosi oko 4 %.

Zbog povećane izgradnje malih hidroelektrana i vjetroelektrana, emisije ugljikovog dioksida u scenariju S2 iznose deset milijuna tona u 2020. godini što je za 12 % manje u odnosu na scenarij S1.

Uz pretpostavku povećanog iskorištenja maksimalne snage elektrana (5 000 sati do 6 000 sati za postojeće/revitalizirane i 7 000 sati za nove proizvodne jedinice), mogućnosti izvoza u scenariju

By the year 2020 a total of 1 284 MW at power plant threshold will start operations, 345 MW of which from hydroelectric power plants (mostly small HPP projects), 250 MW from wind farms and two thermal power plants – Gacko in 2014 and Stanari in 2019.

In the total electricity production, the share of hydroelectric power plants will fall from 44 % at the beginning of the planning period to 39 % in the year 2020. At the same time, the thermal power plant share will remain nearly constant (change from approximately 55% to approximately 57 %). The remainder of the electricity needed will be ensured from import (which ceases after 2011) and from wind farms whose share in total production in 2020 will be approximately 4 %.

Due to increased construction of small hydroelectric power plants and wind farms, the carbon-dioxide emissions in the scenario amount to ten million tonnes in 2020, which is 12 % less than in the S1 scenario.

With the assumption of increased maximum power utilisation of power plants (from 5 000 hours to 6 000

S2 iznose u prosjeku 1 400 GWh/god., a maksimalno do 2 500 GWh/god.

7 ZAKLJUČAK

Rezimirajući cjelokupnu analizu provedenu za plan izgradnje proizvodnih objekata kroz cijelo plansko razdoblje (2009. do 2020. godine), između svih važnih pitanja izdvaja se nekoliko njih, za koje se može reći da su ključna:

— odnos dva entiteta (Federacije BiH i Republike Srpske), zatim odnos tri elektroprivrede, njihova spremnost na suradnju u elektroenergetskom sektoru i pristup planiranju izgradnje elektrana zasnovan na međusobnim odnosima,
— razina elektroenergetske suverenosti Bosne i Hercegovine kao države, njenih entiteta i elektroprivreda pojedinačno (razina samodostatnosti ili mjera oslanjanja na uvoz električne energije, ili pak izvozna orijentacija),
— stanje u elektroenergetskom sektoru zemalja u regiji i mogući utjecaj na buduću izgradnju elektrana u BiH,
— mogućnost izgradnje novih termoelektrana na ugljen, s obzirom na rezerve ugljena i cijenu ugljena,
— mogućnost izgradnje novih hidroelektrana,
— udio novih obnovljivih izvora električne energije (vjetar, male HE, biomasa i sl.) u podmirivanju ukupne potrošnje,
— utjecaj izgradnje novih izvora na stanje okoliša i mogućnost harmonizacije s domaćom i međunarodnom pravnom regulativom koja tretira problem zaštite okoliša.

Dakako da pored gore navedenih pitanja postoje i druga važna pitanja.

Kad se govori o odnosu entiteta i elektroprivreda misli se na njihov pristup planiranju izgradnje elektrana, s jedne strane, i na vođenje ili eksploataciju EES-a s druge strane. Iz područja planiranja poznato je da veći EES treba manje rezervne snage u postotku. Dakako da to ovisi i o mnogim drugim karakteristikama sustava, kao što je veličina agregata, udjel hidroelektrana, njihov faktor iskorištenja snage, udjel termoelektrana-toplana i sl. Ali uz sličnu strukturu sustava, uz slične veličine agregata, svakako da veći sustav treba relativno manju rezervu. Manja potrebna rezerva posljedica je manje vjerojatnosti neplaniranog ispada iz pogona pojedinog agregata i rezultat neistovremenosti vršnog opterećenja u sustavima koje pokriva pojedina elektroprivreda. Zato je i potrebno razmišljati o mogućoj sinergiji kod izgradnje novih elektrana tri elektroprivrede u

hours for existing/revitalised and 7 000 hours for new production units), the export possibilities in the S2 scenario amount to 1 400 GWh/year on average, and 2 500 GWh/year maximum.

7 CONCLUSION

When summarising the analysis performed for the construction plan of production facilities through the entire planning period (2009 – 2020), among all the important issues, several that arise may be called key issues:

— the relationship between two entities (the Federation of Bosnia and Herzegovina and the Republic of Srpska), the relationship between three electric utility companies, their readiness for cooperation in the electric power sector and the approach to planning the construction of power plants based on their mutual relations,
— the level of electric power sovereignty of Bosnia and Herzegovina as a state, its entities and electric utility companies individually (the level of self-sufficiency, the extent of relying on the import of electricity, or the orientation towards export),
— the state of the electric power sector of other countries in the region and the possible influence on the future construction of power plants in Bosnia and Herzegovina,
— the possibility for the construction of new coal-powered thermal power plants, considering coal reserves and prices,
— the possibility for the construction of new hydroelectric power plants,
— the share of new renewable sources of electricity (wind, small hydroelectric power plants, biomass, etc.) in covering the total consumption,
— the influence of the construction of new sources on the state of the environment and the possibility for harmonisation with the national and international legislation regulating the issue of environment protection.

Naturally, there are other important issues in addition to those listed above.

When discussing the relationships of entities and electric utility companies, their approach to power plant construction planning is referred to on one side, and the running or exploitation of the EPS on the other. It is known from planning that a larger EPS needs a smaller percentage of reserve power. Of course, that depends on many other system characteristics, such as generator size, hydroelectric power plant share, their power utilisation factor, the share of thermal power plants-heating plants etc. However, with a similar system structure, with similar generator sizes, a larger system would absolutely need

BiH. Time se ni u kojem slučaju ne dovodi u pitanje slobodna volja svake elektroprivrede, niti bilo kojeg drugog potencijalnog investitora, da prema svojim procjenama odnosa na trenutnom i budućem tržištu električne energije, u samoj BiH i izvan nje, gradi vlastite elektrane. To je, na koncu, jedno od osnovnih postignuća deregulacije.

Postoje dvije moguće krajnosti – prva da sve elektroprivrede grade elektrane prema svojim strategijama ne vodeći računa o tome što rade ostale dvije elektroprivrede i druga – da se zajednički planira izgradnja na način da se utvrdi redoslijed gradnje elektrana prema optimumu na razini BiH, a da se isto tako koordinira pogon elektrana kako bi se elektrane s nižim troškovima pogona koristile što dulje vremena. U ovom drugom slučaju, računajući na razini cijele BiH uštede bi bile dvojake, manje potrebne investicije u izgradnju novih elektrana i manji pogonski troškovi radi boljeg korištenja elektrana.

Najizgledniji je scenarij negdje između te dvije krajnosti.

Ovdje se daje primjer odnosa potrebne izgradnje novih elektrana i ukupnih troškova u EES-u za razdoblje 2009. do 2020. godine, ako bi se u jednom slučaju planiralo na razini cijele BiH, a u drugom slučaju na razini pojedinih elektroprivreda. Za razinu BiH kao cjelinu dovoljno je do 2020. godine izgraditi oko 1 090 MW u novim elektranama, pri čemu su ukupni troškovi (gorivo, održavanje, izgradnja) oko $6\ 620 \cdot 10^{6}$ EUR. U drugom slučaju, kada se planira pojedinačno po elektroprivredama izgradilo bi se oko 2300 MW, a ukupni troškovi u razdoblju 2009. do 2020. godine bili bi oko $8\ 150 \cdot 10^{6}$ EUR. Ovo je dovoljan pokazatelj koje su koristi od suradnje među elektroprivredama u BiH, kada je u pitanju izgradnja novih elektrana a isto tako i kad se radi o pogonu elektrana.

Pitanje razine elektroenergetske suverenosti BiH kao države, zatim njenih entiteta i konačno elektroprivreda pitanje je od iznimne važnosti. Radi se dakle o razini samodovoljnosti svih navedenih subjekata u pogledu podmirivanja potrošnje električne energije. Ili preciznije, koji je to iznos (%) potreba za električnom energijom koji se mora moći podmiriti iz elektrana na vlastitom teritoriju. Treba reći da ima onih koji propagiraju ideju da u uvjetima otvorenog tržišta to pitanje nije toliko bitno. Da se energija, ako je ne možete proizvesti na vlastitom području, može kupiti i dovesti s nekog drugog područja. To je u principu moguće, naravno ako te energije ima uvijek kad je to potrebno i ako su uvjeti u prijenosnoj mreži takvi da je uvijek moguće tu energiju dopremiti. Međutim, vrlo često, barem prema iskustvima u posljednjih nekoliko godina, događa se, da niti jedan od ova

a relatively smaller reserve. The smaller required reserve is a consequence of the decreased probability of an unplanned generator outage and a result of asynchronous peak loads in the systems covered by a certain electric utility company. That is why it is necessary to consider possible synergy in the construction of the new power plants for the three electric utility companies in Bosnia and Herzegovina. That does not in any case call into question the free will of each of the electric utility companies, or any other potential investor, to build their own power plants according to their own estimates of relations on the current and future electricity market in Bosnia and Herzegovina or outside its borders. That is, finally, one of the basic accomplishments of deregulation.

There are two possible extremes – the first is that all electric utility companies build power plants according to their own strategies, not taking into consideration what the other two electric utility companies are doing, and the second – that construction is planned jointly in a way which would determine the order of power plant construction in accordance with the optimum at the level of Bosnia and Herzegovina, and furthermore, that the operations of power plants are coordinated in a manner which would enable the power plants with lower operation costs to be used for longer periods of time. In the second case, when calculating at the level of the entire Bosnia and Herzegovina, the savings would be twofold, the necessary investments for the construction of new power plants would be lower, and so would the operation expenses due to more efficient use of power plants.

The scenario with the best odds is somewhere between these two extremes.

Examples are given of relations between the necessary construction of new power plants and the total EPS costs for the period between 2008 and 2020, if in one case the planning would be at the level of the entire Bosnia and Herzegovina, and in the other, at the level of individual electric utility companies. For the level of Bosnia and Herzegovina as a whole, it would be sufficient to build approximately 1 090 MW of new power plants by 2020, which would place the total costs (fuel, maintenance, construction) to approximately $6\ 620 \cdot 10^{6}$ EUR. In the other case, when the planning would cover individual electric utility companies, approximately 2300 MW would be constructed, and the total costs for the period between 2008 and 2020 would be approximately $8\ 150 \cdot 10^{6}$ EUR. This is a sufficient indicator for the benefits of cooperation between electric utility companies in Bosnia and Herzegovina when the construction of new power plants is concerned, and the same applies for power plant operations.

The issue of the level of electric power sovereignty of Bosnia and Herzegovina as a state, of its entities and, finally, of electric utility companies is a pivotal issue. It concerns the level of self-sufficiency of all the gidva uvjeta nije ispunjen. Postoji i jedan dodatni problem, a to je cijena te električne energije koju se mora kupovati. Ona u određenim okolnostima može biti dosta skuplja (ovdje se govori samo o djelatnosti proizvodnje) od proizvodnih troškova nekih potencijalnih elektrana-kandidata za izgradnju u BiH. Radi svega navedenog, i radi energetskih potencijala BiH, zastupa se mišljenje da se u BiH kao cjelini treba ići na potpunu samodovoljnost u proizvodnji električne energije. To znači graditi toliko elektrana koje će biti u stanju podmiriti ukupne potrebe za električnom energijom u BiH.

Jedno od vrlo važnih pitanja jest treba li u BiH graditi elektrane koje će najvećim dijelom proizvoditi električnu energiju za kupce ili potrošače u drugim zemljama. U svakom slučaju to će ovisiti o poslovnim odlukama potencijalnih investitora, međutim u tome treba biti vrlo oprezan ili u najmanju ruku umjeren. Radi se o strateškim odlukama s dugoročnim posljedicama, osobito ako se radi o termoelektranama na ugljen. Ono što je od posebne važnosti za termoelektrane na ugljen jest dovođenje rudnika u stanje koje će osigurati redovitu opskrbu blokova dovoljnim količinama ugljena. Pitanje je koliko je pametno, a i opravdano ići na maksimalnu izgradnju termoelektrana na ugljen čiji bi se najveći dio proizvodnje izvozio. Veliki dio ležišta bi se tako forsiranom izgradnjom termoelektrana potrošio već u radnom vijeku tih elektrana. Što nakon toga? To nije samo stvar potencijalnih investitora nego o tome, u određenom smislu, trebaju odlučivati i političke strukture ili strukture vlasti u BiH, a u konačnici i sami građani BiH. U svakom slučaju, tako forsirana izgradnja termoelektrana na ugljen bi se teško mogla uklopiti u koncept koji se zasniva na održivom razvoju, odnosno koncept u kojem je održivi razvoj temeljna odrednica.

Mogućnost izgradnje novih hidroelektrana zanimljiva je iz više razloga. Prepoznajući problem klimatskih promjena, uzrokovanih velikim dijelom emisijom stakleničkih plinova kao posljedice ljudskog djelovanja, svijet, a posebno EU, stavlja vrlo veliki naglasak na povećanu proizvodnju energije (i električne) iz obnovljivih izvora. Hidroelektrane (i male i velike) dio su mogućeg rješenja. Stoga su u mnogim zemljama, posebice EU, poduzete određene mjere koje čine ulaganje u sektor malih hidroelektrana dosta atraktivnim. Kad se radi o većim hidroelektranama (preko 10 MW) koje ne ulaze u takve mehanizme poticaja situacija je nešto složenija. Preostali hidroenergetski potencijal u mnogim zemljama još je uvijek skup u odnosu na neke termoelektrane. Međutim, kretanje cijena fosilnih goriva u posljednjim godinama ide na ruku i većim hidroelektranama. Tako u BiH ima nekoliko lokacija gdje je izgradnja hidroelektrana vrlo izgledna i treba učiniti sve

ven subjects in view of settling electricity consumption needs. Or, to be more precise, the amount (%) of electricity requirements that need to be settled from power plants on their own territory. It should be noted that there are those who promote the idea that the issue is not very relevant in open market conditions. That energy, if you cannot produce it on your own territory, can be bought and brought from another territory. That is possible in principle, of course, if the energy is available every time it is needed and if the transmission network conditions are such that energy can always be brought. However, it very frequently happens, at least according to experiences gained in recent years, that neither of the two conditions is met. There is also an additional problem, and that is the price of the electricity which needs to be bought. In some circumstances it can be significantly more expensive (only production activity is discussed here) than production costs of some potential power plant candidates for construction in Bosnia and Herzegovina. Because of everything stated above, and because of the Bosnia-Herzegovina energy potentials, the opinion of many is that Bosnia and Herzegovina as a whole needs to strive for complete self-sufficiency in electricity production. That means building a number of power plants which could settle all electricity needs of Bosnia and Herzegovina.

One of very important issues is whether Bosnia and Herzegovina should build power plants which would for the most part produce electricity for buyers or consumers from other countries. In any case, it will depend on business decisions of potential investors. However, extreme caution, or at least moderation, should be exercised in that respect. Those are strategic decisions with long-term effects, especially if coal-powered thermal power plants are concerned. The crucial matter concerning coal-powered thermal power plants is bringing coal mines to a state which would ensure regular supply of sufficient quantities of coal to the blocks. The question arises whether it is smart, or justified, to opt for the maximum construction of coal-powered thermal power plants which largest production share would be exported. A large part of the deposits would, with such a forced thermal power plant construction, be spent in the operation span of those power plants. What would happen afterwards? It is not a matter which should concern only the potential investors. In a certain sense the issue also needs to be decided upon by the political structures or the government structures in Bosnia and Herzegovina, and finally by its citizens themselves. In any case, such a forced construction of coal-powered thermal power plants could hardly fit into the concept founded on the principles of sustainable development, or the concept where sustainable development is the baseline.

The construction possibilities of new hydroelectric power plants are interesting for several reasons. When recognising the climate change issue, caused da bi se stvorila prihvatljiva poduzetnička klima kako bi se one što prije počele graditi odnosno kako bi se što prije pustile u pogon. Za sada je u gradnji samo HE Mostarsko Blato, ali ima još nekoliko lokacija koje su već sazrele za gradnju. Na ostalim lokacijama koje imaju realne izglede za gradnju treba napraviti potrebne istražne radove i polaznu tehničku dokumentaciju, kako bi se raspolagalo s preciznijim podacima o mogućoj proizvodnji, odnosno instaliranoj snazi i investicijskim troškovima. To je vrlo bitna podloga za odluku potencijalnih investitora: financirati ili ne financirati gradnju pojedine hidroelektrane.

Udio obnovljivih izvora u proizvodnji električne energije pitanje je koje sve više dobiva na težini. Tako se i u zemljama EU donose razni akti (direktive) kojima se nastoji stvoriti prostor za izgradnju što više obnovljivih izvora električne energije. Kao što je poznato u tu kategoriju se ne ubrajaju velike hidroelektrane (veće od 10 MW).

Budući da se proizvodni trošak električne energije iz vjetroelektrana gotovo izravnao s troškom iz do sada tzv. konvencionalnih izvora, u scenariju koji s najviše optimizma tretira korištenje obnovljivih izvora (scenarij S2), očekuje se do 2020. godine izgradnja oko 250 MW u vjetroelektranama (uglavnom EP HZHB). U 2020. godini to bi bilo oko 4 % ukupne proizvodnje električne energije. Za druge obnovljive izvore, kao što su male hidroelektrane, biomasa, sunce i ostali, nije realno očekivati veću penetraciju bez stimulativnih mjera države kojima bi se stvorilo pozitivno okruženje za korištenje obnovljivih izvora. Pretpostavljajući skoro uvođenje takvih mjera, može se uz vrlo veliki optimizam očekivati izgradnja do 280 MW malih hidroelektrana u cijeloj BiH. Udio proizvodnje u malim hidroelektranama u ovakvom scenariju iznosio bi 5 % do 6 % u ukupnoj potrošnji električne energije u BiH. Biomasa i solarna energija nisu razmatrane u nekoj značajnijoj zastupljenosti u proizvodnji električne energije. Rezimirajući sve do sada navedeno u vezi obnovljivih izvora električne energije, može se reći da uz vrlo aktivne mjere države, u smislu konkretne financijske potpore proizvođačima električne energije iz obnovljivih izvora, ne treba očekivati udjel tih izvora veći od 5 % do 10 % do 2020. godine. Iz ovoga su, naravno, isključene velike hidroelektrane.

Utjecaj energetskog sektora na okoliš, gdje posebnu pozornost zaslužuju klimatske promjene kao posljedica efekta staklenika, postalo je pitanje od najviše razine prioriteta u većini zemalja svijeta, a napose u zemljama EU. Kad se govori o elektroenergetskom sektoru, najvažniji su problem elektrane na fosilna goriva, a među njima svakako termoelektrane na ugljen. Dok se za ostale onečišćujuće tvari (NO_x, SO_x, če-

in the most part by greenhouse gas emissions from human actions, the world, and especially the EU, places great emphasis on the increased energy (and electricity) production from renewable sources. Hydroelectric power plants (small and large ones) are part of the possible solution. Therefore, in many countries, especially of the EU, certain measures have been undertaken which make the investment in the small hydroelectric power plant sector quite attractive. When larger hydroelectric power plants (over 10 MW), ineligible for such incentives, are concerned, the situation is somewhat more complex. The remaining hydropower potential in many countries is still expensive when compared to certain thermal power plants. However, the fluctuations in fossil fuel prices in recent years also benefit the large hydroelectric power plants. There are several locations in Bosnia and Herzegovina where the construction of hydroelectric power plants is highly probable, and all necessary steps must be taken to create an acceptable entrepreneurial climate for their construction or their prompt start of operations. Presently, only HPP Mostarsko Blato is in construction, but there are several other locations ready for construction. Necessary research needs to be undertaken and the initial technical documentation needs to be compiled for other locations with realistic chances of construction, in order to have the use of precise data on possible production, installed power and investment costs. It is a crucial base for the decision of potential investors: to finance or not to finance the construction of a certain hydroelectric power plant.

The share of renewable sources in electricity production is the issue gaining increasing importance. The EU states are enacting various legislations (directives) which try to create space for the construction of renewable electricity sources. That category does not include large hydroelectric power plants (larger than 10 MW).

Since the production cost of electricity from wind farms has nearly equalled the cost from the heretofore so-called conventional sources, the scenario which treats the use of renewable sources with most optimism (scenario S2) expects the construction of approximately 250 MW of wind farms until the year 2020 (predominantly EP HZHB). In 2020 that would amount to approximately 4 % of total electricity production. For other renewable sources, such as small hydroelectric power plants, biomass, the sun and others, a larger penetration is not realistically expected without state incentive measures which would create a positive environment for the use of renewable sources. If we assume an imminent introduction of such measures, the construction of up to 280 MW of small hydroelectric power plants can be expected in the entire Bosnia and Herzegovina with great optimism. The production share of small hydroelectric power plants in such a scenario would be 5 % to 6 % of the total electricity consumption in Bosnia and stice) može reći da je njihovu emisiju moguće svesti u prihvatljive okvire, za CO_2, kao glavnog predstavnika stakleničkih plinova, za sada nema rješenja. Značajnije komercijalno korištenje CCS (engl. *Carbon Capture and Storage*) tehnologija, prema današnjim sagledavanjima, ne očekuje se prije 2020. godine. Određenje o pitanju emisije CO_2 u BiH u ovom trenutku nije nimalo lako. Naime, BiH nema obveze smanjenja emisije u odnosu na Kyoto protokol. Međutim, postojeći okvir ili obveze Kyoto protokola su na snazi do kraja 2012. godine i još uvijek nije jasno kakav će biti sljedeći korak. Ono što je sigurno je to da je u pripremi novi sporazum koji će uključiti dodatno i zemlje koje nisu obveznice Kyoto protokola, što znači vrlo vjerojatno i BiH. S druge strane BiH nema još izrađen NAP-a (Nacionalni alokacijski plan), koji bi trebao definirati emisijske kvote za sve subjekte koji bi tim planom bili obuhvaćeni. Tim će planom, dakle, biti definirane i emisijske kvote pojedine elektroprivrede u BiH, a to znači da će i svaka termoelektrana na ugljen imati svoju emisijsku kvotu. Svemu ovome relativno skoro treba dodati i mogućnost trgovanja emisijskim dozvolama, kakva je mogućnost u zemljama EU uvedena od početka 2005. godine. Iz navedenog se može zaključiti da postoji još dosta nepoznanica vezanih uz problem emisija CO_2 iz postojećih i budućih termoelektrana u BiH. O tome trebaju voditi računa i budući investitori u termoelektrane na ugljen u BiH. To je jedna od komponenti rizika koja mora biti ukalkulirana u strateške odluke vlasnika postojećih i budućih termoelektrana na ugljen.

Ukupni koncept na kojem je zasnovana izrada ovih scenarija ponajprije vodi računa o pokrivanju vlastitih potreba za električnom energijom, bilo da se radi na razini države, entiteta ili pojedine elektroprivredne tvrtke. Iz te činjenice proizlaze i neka drukčija sagledavanja buduće izgradnje elektrana. Kad se pokušava doslovno slijediti pristup odozdo prema gore, nailazi se na problem uklapanja svih elektrana, koje su u planovima pojedine elektroprivrede, u elektroenergetski sustav BiH. Stoga treba imati na umu da jedan dobar dio potencijalnih kandidata za izgradnju mora naći sebi tržište izvan BiH.

Herzegovina. Biomass and solar power are not considered as having a significant presence in electricity production. Summarising everything stated so far in connection with renewable electricity sources, it can be said that even with very active state measures, in the sense of tangible financial support of renewable source electricity producers, a share of those sources higher than 5 % to 10 % before 2020 should not be expected. This, naturally, excludes large hydroelectric power plants.

The influence of the electric power sector on the environment, where climate changes due to the consequences of the greenhouse effect deserve special attention, has become the top priority issue in most countries of the world, and especially in the EU states. When the electric energy sector is concerned, the biggest problem are fossil-fuel-powered power plants, and among them undoubtedly coal-powered thermal power plants. While it can be said that the emissions of other pollutant substances (NO_x, SO_x, particles) can be reduced to acceptable levels, presently there is still no solution for CO_2, the main representative of greenhouse gasses. A more significant commercial usage of CCS (Carbon Capture and Storage) technologies, by today's observations, is not expected before 2020. Tackling the CO_2 emissions issue in Bosnia and Herzegovina at this time is not easy by any means. Namely, Bosnia and Herzegovina is not obligated to reduce emissions in accordance with the Kyoto protocol. However, the existing framework or obligations of the Kyoto protocol are in force until the end of 2012 and it is still not clear what the next step will be. What is certain is that a new agreement is being prepared which will additionally include the countries not committed to the Kyoto protocol, and therefore it will very likely include Bosnia and Herzegovina. On the other hand, Bosnia and Herzegovina has still not composed a NAP (National Allocation Plan), which should define the emission quotas for all subjects encompassed by the plan. The plan will, therefore, also define the emission quotas for individual electric utility companies in Bosnia and Herzegovina, which means that every coal-powered thermal power plant will have its own emission quota. A possibility of emission permits trade which was introduced into EU states in early 2005 will need to be added to all of this relatively soon. From everything stated above it can be concluded that there are still many unknowns tied to the CO_2 emissions problem from the existing and future thermal power plants in Bosnia and Herzegovina. The future investors in coal-powered thermal power plants in Bosnia and Herzegovina will need to take that into consideration. It is one of the risk components which needs to be calculated into the strategy decisions of the owners of existing and future coal-powered thermal power plants.

The overall concept on which the compiling of these scenarios is based firstly takes into account the covering of electricity needs pertaining to either the state, an entity or an individual electric utility company. Other, different observations of the future power plant construction stem from that fact. When attempts are made to follow the bottom-up approach ad litteram, a problem arises when integrating all power plants contained in individual electric utility company plans, into the electric power system of Bosnia and Herzegovina. Therefore, it should be born in mind that a significant portion of potential candidates for construction will need to find themselves a market outside Bosnia and Herzegovina.

LITERATURA / REFERENCES

[1] Studija energetskog sektora BiH, Međunarodni konzorcij: Energetski institut Hrvoje Požar, Ekonomski institut Banjaluka, Rudarski institut Tuzla, Soluziona (Španjolska), 2008.

[2] Update of Generation Investment Study, South East Europe Consultants, Ltd., Washington, Belgrade, January 31, 2007

[3] Expansion Planning for Electrical Generating Systems, A Guidebook, Technical Reports Series No. 241, IAEA 1984

Adrese autora:

Doc. dr. sc. **Mladen Zeljko**
mzeljko@eihp.hr
Energetski institut Hrvoje Požar
Savska cesta 163
10000 Zagreb
Hrvatska

Authors' Adresses:

Assistant Prof. **Mladen Zeljko**, PhD
mzeljko@eihp.hr
Energy Institute Hrvoje Požar
Savska cesta 163
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2009-09-11

Prihvaćeno:
2009-09-23

Manuscript received on:
2009-09-11

Accepted on:
2009-09-23

ENERGETSKA CERTIFIKACIJA ZGRADA I SUVREMENI ENERGETSKI KONCEPTI

ENERGY CERTIFICATION OF BUILDINGS AND MODERN ENERGY CONCEPTS

Željka Hrs Borković, Zagreb, Hrvatska

Uvođenje energetske certifikacije zgrada u hrvatsko zakonodavstvo i podjele zgrada u energetske razrede prema godišnjoj potrebnoj toplinskoj energiji za grijanje donosi niz ključnih promjena u graditeljstvu, koje će odigrati značajnu ulogu kako u povećanju kvalitete gradnje i osmišljavanju suvremenog energetskog koncepta novih zgrada te osuvremenjivanju postojećih zgrada, tako i u značajnom doprinosu smanjenju energetske potrošnje u sektoru zgradarstva, kao najvećem pojedinačnom potrošaču energije.

U radu se prikazuje novi zakonodavni okvir i metodologija provedbe energetskih pregleda i energetske certifikacije zgrada u Republici Hrvatskoj (RH), te očekivani utjecaj na razvoj integralnog pristupa projektiranju i dugoročnog pristupa analizi zgrade, uzimajući u obzir njezin cijeli životni vijek. Energetskim certificiranjem zgrada dobivaju se transparentni podaci o potrošnji energije u zgradama na tržištu, energetska učinkovitost prepoznaje se kao znak kvalitete, potiču se ulaganja u nove inovativne koncepte i tehnologije, potiče se korištenje alternativnih sustava za opskrbu energijom u zgradama, razvija se tržište novih nisko energetskih zgrada i modernizira sektor postojećih zgrada, te se doprinosi ukupnom smanjenju potrošnje energije i zaštiti okoliša.

The introduction of energy certification of buildings in Croatian legislature and the classification of buildings in energy classes in accordance with their annual thermal energy requirements for heating purposes introduces a number of key changes in construction. They will play a considerable role in the improvement of construction quality, creation of a modern energy concept for new buildings, modernisation of existing buildings, and will significantly contribute to the reduction of energy consumption in the building construction sector, the latter being the largest individual energy consumer.

This paper presents the new legislative framework and the implementation methodology for energy audits and energy certification of buildings in the Republic of Croatia (RH), and it elaborates on the expected influence on the development of the integral approach to design and the long term approach to building analysis, taking into consideration the entire lifespan of the building. Energy certification of buildings provides us with transparent data on energy consumption in buildings on the market, energy efficiency is recognised as an indication of quality, investments in new and innovative concepts and technologies are encouraged, as is the use of alternative energy supply systems in buildings, the market for new low-energy buildings develops, the existing buildings sector is modernised, and a contribution is made towards a general reduction of energy consumption and towards environment protection.

Ključne riječi: energetska certifikacija zgrada; energetska učinkovitost; energetski koncept; integralno projektiranje

Keywords: energy certification of buildings; energy concept; energy efficiency; integral design

1 UVOD

Implementacijom EU Direktive 2002/91/EC o energetskim svojstvima zgrada (EPBD) [1] u hrvatsko zakonodavstvo se uvodi obvezna energetska certifikacija zgrada za nove i postojeće zgrade. EPBD se implementira na temelju Akcijskog plana za implementaciju [2] izrađenog u Ministarstvu zaštite okoliša, prostornog uređenja i graditeljstva (MZOPUG) i usvojenog u travnju 2008. godine, kroz Zakon o prostornom uređenju i gradnji (NN 76/2007 i 38/2009 članak 15.) [3] te putem niza tehničkih propisa i pravilnika, od kojih su do sada usvojeni: Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti zgrada (NN 110/2008 i 89/2009) [4], Tehnički propis o sustavima grijanja i hlađenja zgrada (NN 110/2008) [5], Pravilnik o energetskom certificiranju zgrada (NN 113/2008 i 91/2009) [6] i Pravilnik o uvjetima i mjerilima za osobe koje provode energetske preglede i energetsko certificiranje zgrada (NN 113/2008 i 89/2009) [7]. U lipnju 2009. godine usvojena je i nacionalna Metodologija provođenja energetskog pregleda zgrada [8], u skladu s člankom 28. Pravilnika [6], čime su ostvareni osnovni preduvjeti za početak energetske certifikacije zgrada.

2 FORMIRANJE ZAKONODAVNOG OKVIRA ZA ENERGETSKE PREGLEDE I ENERGETSKU CERTIFIKACIJU ZGRADA

Energetski certifikat zgrade jest dokument koji predočuje energetska svojstva zgrade i koji ima propisani sadržaj i izgled prema pravilniku [6], a izdaje ga ovlaštena osoba. Vrijednosti koje su istaknute na energetskom certifikatu odražavaju energetska svojstva zgrade i potrošnju energije izračunatu na temelju pretpostavljenog režima korištenja zgrade i ne moraju nužno izražavati realnu potrošnju u zgradi ili njezinoj samostalnoj uporabnoj jedinici, jer ona uključuje i ponašanje korisnika. Energetski pregled zgrade jest dokumentirani postupak koji se provodi s ciljem utvrđivanja energetskih svojstava zgrade i stupnja ispunjenosti tih svojstava u odnosu na zahtjeve propisane posebnim propisima i sadrži prijedlog mjera za ekonomski povoljno poboljšanje energetskih svojstava zgrade, a provodi ga ovlaštena osoba. Temeljem provedenog energetskog pregleda i izračunatih energetskih potreba zgrade izrađuje se energetski certifikat.

Ujedno, energetski certifikat jest i jaki marketinški instrument s ciljem promocije energetske učinkovitosti i nisko energetske gradnje i postiza-

1 INTRODUCTION

With the implementation of the EU Directive 2002/91/EC on the energy performance of buildings (EPBD) [1] the obligatory energy certification of new and existing buildings is introduced into Croatian legislature. EPBD is implemented on the basis of the Implementation Action Plan [2] compiled by the Ministry of Environmental Protection, Physical Planning and Construction (MZOPUG) and adopted in April 2008 with the Physical Planning and Building Act (Official Gazette of the Republic of Croatia 76/07 and 38/09 Article 15) [3] and through a series of technical regulations and ordinances adopted so far: the Technical Regulation on Energy Economy and Heat Retention in Buildings (Official Gazette of the Republic of Croatia 110/08 and 89/09) [4], the Technical Regulations on the Heating and Cooling Systems of Buildings (Official Gazette of the Republic of Croatia 110/08) [5], the Ordinance on Energy Certification of Buildings (Official Gazette of the Republic of Croatia 113/08 and 91/09) [6], the Ordinance on the Requirements and Criteria to be met by Energy Auditors and Energy Certifiers of Buildings (Official Gazette of the Republic of Croatia 113/08 and 89/09) [7]. In June 2009, the national Implementation Methodology for the Energy Audits of Buildings [8] was also adopted, in accordance with Article 28 of the Ordinance [6], which realised the basic preconditions for the start of the energy certification of buildings.

2 THE FORMATION OF THE LEGISLATIVE FRAMEWORK FOR ENERGY AUDITS AND ENERGY CERTIFICATION OF BUILDINGS

The energy certificate of a building is a document which presents the energy performance of a building, which has the content and appearance prescribed by the Ordinance [6], and is issued by an authorised person. The values presented in the energy certificate reflect the energy performance of a building and the energy consumption calculated on the basis of an assumed regime of building use. They do not necessarily need to reflect the real consumption of the building or its independent usage unit because the latter also includes the behaviour of the users. The energy audit of a building is a documented procedure implemented to determine the energy performance of a building and the degree of performance fulfilment in relation to the requirements prescribed by special regulations. It contains a suggestion of the measures for a financially favourable improvement of the energy performance of a building and it is performed by an authorised person. The energy certificate is compiled based on the performed energy audit and the nja višeg komfora života i boravka u zgradama. Energetskim certificiranjem zgrada dobivaju se transparentni podaci o potrošnji energije u zgradama na tržištu, energetska učinkovitost prepoznaje se kao znak kvalitete, potiču se ulaganja u nove inovativne koncepte i tehnologije, potiče se korištenje alternativnih sustava za opskrbu energijom u zgradama, razvija se tržište novih nisko energetskih zgrada i modernizira sektor postojećih zgrada, te se doprinosi ukupnom smanjenju potrošnje energije i zaštiti okoliša.

Pravilnik [6] propisuje zgrade za koje je potrebno izdati energetski certifikat, energetske razrede zgrada, sadržaj i izgled energetskog certifikata, energetsko certificiranje novih i postojećih zgrada, obveze zgrada javne namjene, postupak energetskog certificiranja, te vođenje registra izdanih energetskih certifikata. Temeljem izračuna specifične godišnje potrebne toplinske energije za grijanje Q_{Hndref} zgrada se svrstava u razred energetske potrošnje, od A+ razreda s najmanjom potrošnjom toplinske energije za grijanje ($Q_{Hndref} \leq 15$ kWh/(m²a)), do G razreda zgrade s najvećom energetskom potrošnjom ($Q_{Hndref} > 250$ kWh/(m²a)) i to u dvije referentne klime: 2 900 stupanj dana grijanja za kontinentalnu Hrvatsku i 1 600 stupanj dana grijanja za primorsku Hrvatsku, s granicom na 2 200 stupanj dana grijanja. Pri tome je važno napomenuti da zgrade projektirane u skladu s tehničkim propisom [4] ulaze u razred energetske potrošnje C, te da je potrebno značajno poboljšanje energetskih svojstava zgrade kako bi zgrada bila svrstana u energetski razred A ili A+.

calculated energy requirements of the building.

The energy certificate is also a strong marketing instrument with the purpose of promoting energy efficiency, low-energy construction and the achievement of greater comfort of living and residing in buildings. Transparent data on energy consumption in buildings on the market are gained by energy certification of buildings, energy efficiency is recognised as an indication of quality, investments in new and innovative concepts and technologies are encouraged, as is the use of alternative energy supply systems in buildings, the market for new low-energy buildings develops, the existing buildings sector is modernised, and a contribution is made to a general reduction of energy consumption and to environment protection.

The Ordinance [6] prescribes the buildings for which it is necessary to issue the energy certificate, the energy classes of buildings, the contents and the appearance of the energy certificate, energy certification of new and existing buildings, the obligations of public use buildings, the procedure of energy certification and the management of the registry of issued energy certificates. Based on the calculations of specific yearly thermal energy requirements for heating $Q_{H,nd,ref}$ buildings are classified in energy consumption classes, from the A+ class with the smallest thermal energy consumption for heating ($Q_{H,nd,ref} \leq 15$ kWh/(m²a)), to the G class with the greatest energy consumption ($Q_{H,nd,ref} > 250$ kWh/(m²a)) in two reference climates: 2 900 heating degree days for inland Croatia and 1 600 heating degree days for seaboard Croatia, with a 2 200 heating degree days limit. It is important to point out that the buildings designed in accordance with the technical regulations [4] belong to the energy consumption class C, and a significant improvement of the energy performance of the buildings is necessary for the building to be classified in the energy class A or A+.

Tablica 1 – Energetski razredi zgrada utvrđeni Pravilnikom [6]
Table 1 – Energy classes of buildings determined by the Ordinance [6]

Energetski razred / Energy class	$Q_{H,nd,ref}$ – specifična godišnja potrebna toplinska energija za grijanje / – specific yearly thermal energy required for heating, 250 kWh/(m²a)
A+	≤ 15
A	≤ 25
B	≤ 50
C	≤ 100
D	≤ 150
E	≤ 200
F	≤ 250
G	> 250

Energetskim certificiranjem zgrada uvodi se:

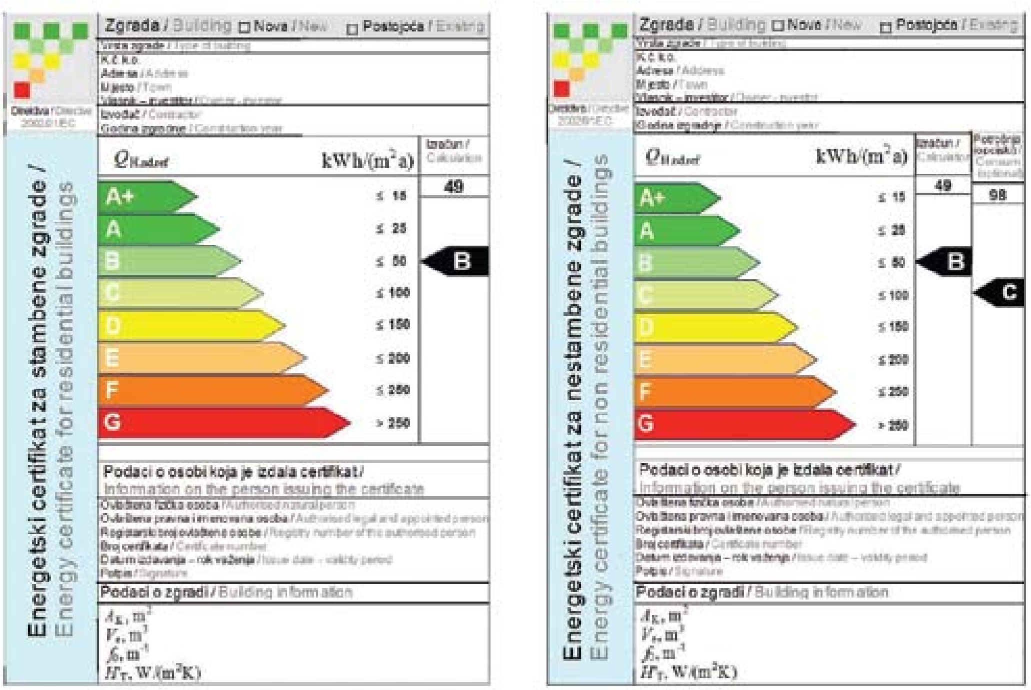
— obveza vlasnika zgrade da prigodom izgradnje, prodaje ili iznajmljivanja zgrade predoči budućem vlasniku odnosno potencijalnom kupcu ili najmoprimcu certifikat o energetskim svojstvima zgrade kojemu rok valjanosti nije duži od deset godina,
— obveza izdavanja i izlaganja energetskog certifikata ne starijeg od 10 godina na jasno vidljivom mjestu, za zgrade javne namjene ukupne korisne površine veće od $1\,000$ m^2 koje koriste tijela javne vlasti i zgrade institucija koje pružaju javne usluge velikom broju ljudi.

Investitor nove zgrade dužan je osigurati energetski certifikat zgrade prije obavljanja tehničkog pregleda, odnosno priložiti ga zahtjevu za izdavanje uporabne dozvole. Ta se obveza odnosi na sve nove zgrade za koje se nakon 31. ožujka 2010. godine podnosi zahtjev za izdavanje akta temeljem kojega se može graditi (građevinske dozvole ili potvrde glavnog projekta), odnosno na sve nove zgrade čija građevinska (bruto) površina nije veća od 400 m^2 i zgrade za obavljanje isključivo poljoprivrednih djelatnosti čija građevinska (bruto) površina nije veća od 600 m^2, za koje je prijavljen početak građenja nakon 31. ožujka 2010. godine.

The energy certification of buildings introduces:

— the obligation of the building owner to present the energy performance certificate of the building, with a validity period of up to ten years, to the future owner, potential buyer or tenant during construction, sale or leasing of the building,
— the obligation, for public use buildings with a total useful area larger than $1\,000$ m^2 used by public authorities, and buildings of institutions providing public services to a large number of people, to issue and display the energy certificate not older than 10 years in a clearly visible place.

The investor in a new building is obliged to ensure the energy certificate of the building before the technical inspection is performed, or enclose it with the request for the issuing of the building inspection certificate. The obligation applies to all new buildings for which the request for the issuing of the document on the basis of which construction can begin (building permit or validation of the main project) is submitted after March 31st 2010, or for all new buildings with a construction (gross) area under 400 m^2 and buildings for exclusively agricultural activities with a construction (gross) area under 600 m^2, for which the start of construction work has been reported after March 31st 2010.



Slika 1 — Prva stranica energetskog certifikata za stambene i nestambene zgrade
Figure 1 — The first page of the energy certificate for residential and non residential buildings

Vlasnik postojeće zgrade dužan je prilikom prodaje ili iznajmljivanja zgrade u cjelini ili njezinog dijela koji je samostalna uporabna cjelina (pojedini stan, pojedinačni uredski prostor i sl.), odnosno lizinga (engl. *leasing*), osigurati energetski certifikat zgrade odnosno njezinog dijela i dati ga na uvid potencijalnom kupcu ili unajmljivaču zgrade. Kod prodaje zgrade ili njezinog dijela koji je samostalna uporabna cjelina, energetski certifikat mora biti na uvidu prigodom sklapanja ugovora o kupoprodaji i sastavni je njegov dio. Sve postojeće zgrade koje se prodaju, iznajmljuju ili daju na lizing moraju imati energetski certifikat dostupan na uvid kupcu ili najmoprimcu najkasnije danom pristupanja Republike Hrvatske u članstvo EU.

Zgrade javne namjene koje imaju ukupnu korisnu površinu veću od $1\ 000\ m^2$ moraju imati energetski certifikat izložen na mjestu jasno vidljivom posjetiteljima zgrade. Energetski certifikat se izrađuje uvećan na format A3, zaštićen od eventualnih oštećenja i pričvršćen na siguran način. Javno se izlaže prva strana energetskog certifikata koja sadrži osnovne podatke o zgradi i skalu energetskih razreda, te treća strana certifikata koja sadrži preporuke za poboljšanje energetskih svojstava zgrade. Zgrade javne namjene, za koje je obvezno javno izlaganje energetskog certifikata, moraju imati izrađen i javno izložen energetski certifikat i popis mjera za povećanje energetske učinkovitosti u roku od najdulje 36 mjeseci od donošenja Metodologije provođenja energetskih pregleda zgrade [8], dakle najkasnije do lipnja 2012. godine.

Energetski certifikat zgrade (stambene i nestambene) sadrži ukupno pet stranica, od kojih prva (slika 1) sadrži osnovne podatke o zgradi te grafičku skalu energetskih razreda od A+ do G s navedenim iznosom specifične godišnje potrebne toplinske energije za grijanje Q_{Hndref} ,$kWh/(m^2a)$. Druga stranica certifikata sadrži klimatske podake, podatke o svim ugrađenim tehničkim sustavima u zgradi, te rezultate izračuna energetskih potreba zgrade s navedenim vrijednostima koeficijenata prolaska topline za pojedine građevne dijelove zgrade. Treća stranica sadrži prijedlog mjera za poboljšanje energetskih svojstava zgrade koje su ekonomski opravdane. Četvrta stranica energetskog certifikata zgrade sadrži objašnjenje tehničkih pojmova, a peta stranica energetskog certifikata zgrade sadrži detaljan opis propisa, normi i proračunskih postupaka za određivanje podataka navedenih u energetskom certifikatu.

The owner of an existing building must ensure the energy certificate of the building or its parts for the sale or rental of the building as a whole, of its part which is an independently usable unit (an individual apartment, an individual office space, etc.), or for leasing, and present it to the potential buyer or renter of the building. During the sale of a building or its part which is an independently usable unit, the energy certificate must be made available for the stipulation of the sales contract and be its integral part. All existing buildings for sale, rent or leasing must have the energy certificate and be able to present it to a buyer or renter at the latest by the date when the Republic of Croatia joins the EU.

Public use buildings with a total useful area larger than $1\ 000\ m^2$ must display the energy certificate in a place clearly visible to all the building visitors. The energy certificate is enlarged into the A3 format, protected from possible damage and fastened in a secure manner. The publicly displayed pages of the energy certificate are the first page, containing the basic data on the building and the energy classes scale, and the third page, containing recommendations for improvements of the energy performance of the building. The public use buildings, for which the public display of the energy certificate is obligatory, must have their energy certificate and the list of measures for increasing energy efficiency compiled and publicly displayed within, at the most, 36 months from the adoption of the Implementation Methodology for the Energy Audits of Buildings [8], that is by June 2012 at the latest.

The energy certificate of a building (residential and non residential) contains a total of five pages, the first of which (figure 1) contains the basic information on the building and the graphic scale of energy classes from A+ to G with the given amount of specific yearly thermal energy requirements for heating $Q_{H,nd,ref}$ in $kWh/(m^2a)$. The second page of the certificate contains climate information, information on all technical systems installed in the building, and the calculation results of the building's energy requirements with the given values of the heat transfer coefficient for certain structural elements of the building. The third page contains the proposed measures for the improvement of the economically justified energy performances of the building. The fourth page of the energy certificate of the building contains the explanation of technical notions, and the fifth page of the energy certificate of the building contains a detailed description of the regulations, standards and calculation procedures to determine the information given in the energy certificate.

3 METODOLOGIJA ENERGETSKIH PREGLEDA ZGRADA

Postupak energetskog certificiranja zgrade sastoji se od:

- energetskog pregleda zgrade,
- vrjednovanja i/ili završnog ocjenjivanja radnji energetskog pregleda zgrade,
- izdavanja energetskog certifikata zgrade.

Radi ujednačavanja kvalitete i metoda provedbe energetskih pregleda zgrada, u lipnju 2009. godine usvojena je nacionalna metodologija [8]. Prema toj metodologiji, energetski pregled zgrade obvezno uključuje:

- analizu građevinskih karakteristika zgrade u smislu toplinske zaštite (analizu toplinskih karakteristika vanjske ovojnice zgrade),
- analizu energetskih svojstava sustava grijanja i hlađenja,
- analizu energetskih svojstava sustava klimatizacije i ventilacije,
- analizu energetskih svojstava sustava za pripremu potrošne tople vode,
- analizu energetskih svojstava sustava potrošnje električne energije – sustav elektroinstalacija, rasvjete, kućanskih aparata i drugih podsustava potrošnje električne energije,
- analizu upravljanja svim tehničkim sustavima zgrade,
- potrebna mjerenja gdje je to nužno za ustanovljavanje energetskog stanja i /ili svojstava,
- analizu mogućnosti promjene izvora energije,
- analizu mogućnosti korištenja obnovljivih izvora energije i učinkovitih sustava,
- prijedlog ekonomski povoljnih mjera poboljšanja energetskih svojstava zgrade, ostvarive uštede, procjenu investicije i jednostavni period povrata,
- izvješće s preporukama za optimalni zahvat i redoslijed prioritetnih mjera koje će se implementirati kroz jednu ili više faza.

Energetski pregled zgrade opcionalno može uključivati i druge radnje, ovisno o namjeni i vrsti zgrade, kao npr. analizu potrošnje sanitarne vode i preporuke za smanjenje potrošnje sanitarne vode.

Osnovna karakteristika energetskog pregleda stambene zgrade je prikupljanje podataka o zgradi i izračun godišnjih energetskih potreba za grijanje i potrošnu toplu vodu, prema HRN EN 13790:2008 [9]. Za stambene zgrade nije obvezno mjerenje niti prikupljanje podataka o potrošnji i troškovima za

3 THE METHODOLOGY FOR THE ENERGY AUDITS OF BUILDINGS

The energy certification procedure of a building consists of:

- the energy audit of the building,
- the valuation and/or final assessment of the energy audit of the building,
- the issuing of the energy certificate of the building.

National methodology [8] was adopted in June 2009 to standardise the quality and methods of the implementation of energy audits of buildings. In accordance with the methodology, the energy audit of a building must include:

- the analysis of the construction characteristics of the building in the sense of heat retention (the analysis of the thermal characteristics of the external envelope of the building),
- the analysis of the energy performance of heating and cooling systems,
- the analysis of the energy performance of air condition and ventilation,
- the analysis of the energy performance of the consumable hot water preparation system,
- the analysis of the energy performance of the electricity consumption system – the system of electrical installations, lighting, household appliances and other subsystems of electricity consumption,
- the analysis of the management of all technical systems of the building,
- the necessary measurements where they are essential to determine energy conditions and/or performances,
- the analysis of possibilities of energy source changes,
- the analysis of the possibilities of energy usage from renewable sources and efficient systems,
- the proposal of economically favourable measures for the improvement of the energy performance of a building, feasible savings, investment estimates and a simple pay back period,
- the report containing recommendations for the optimal intervention and the order of priority measures which will be implemented through one or more phases.

The energy audit of a building can optionally include other actions, depending on the use and type of the building, for example, the consumption analysis for the water for sanitary use and recommendations for the reduction of the consumption of water for sanitary use.

The basic characteristic of the energy audit of a residential building is the gathering of data on the energiju, već se cijeli energetski pregled temelji na prikupljanju ulaznih podataka i izračunu. Ukoliko postoje podaci, moguće je opcionalno analizirati i potrošnju i troškove za energiju te provesti određena mjerenja radi utvrđivanja kvalitete izvedbe kod novih zgrada, odnosno identifikacije problema i točnijeg utvrđivanja energetskih svojstava kod postojećih zgrada.

Kod energetskog pregleda nestambenih zgrada treba voditi računa o karakteristikama potrošnje energije u zgradama određene namjene. Kao i kod stambenih zgrada, prikupljaju se potrebni ulazni podaci radi utvrđivanja energetskih svojstava zgrade, te se temeljem prikupljenih podataka provodi izračun godišnjih energetskih potreba za grijanje i potrošnu toplu vodu, prema [9]. Za nestambene zgrade mogu se analizirati troškovi za energiju i po potrebi modelirati energetska potrošnja i to:

— troškovi za električnu energiju i karakteristike potrošnje,
— troškovi za toplinsku energiju i karakteristike potrošnje,
— troškovi za sanitarnu vodu i karakteristike potrošnje.

Optimalno se analiza troškova provodi za period od tri godine, odnosno 36 mjeseci.

Za preciznije utvrđivanje postojećih energetskih svojstava zgrade i svih tehničkih sustava u zgradi često je potrebno provesti određena mjerenja. Kada postoji opravdana sumnja u točnost ulaznih podataka potrebnih za izračun energetskih svojstava vanjske ovojnice i tehničkih sustava, mogu se provoditi mjerenja:

— toplinskih gubitaka kroz vanjsku ovojnicu (slike 2 i 3) korištenjem infracrvene termografije (ICT), te mjerenje zrakopropusnosti (Blower Door Test), mjerenje toplinskog otpora,
— u sustavima klimatizacije, grijanja, hlađenja, ventilacije,
— elektroenergetskih parametara potrošnje električne energije – po trošilima ili podsustavima.

building and the calculation of yearly energy requirements for heating and consumable hot water, in accordance with HRN EN 13790:2008 [9]. The measuring or collecting data on consumption and energy costs is not obligatory for residential buildings, since the entire energy audit is based on gathering input data and calculations. If data exist, it is optionally possible to analyse both the consumption and the energy costs and undertake certain measurements to ascertain the quality of execution in new buildings, or identify the problems and more accurately determine the energy performances of existing buildings.

When performing energy audits of non residential buildings, the energy consumption characteristics in buildings for specific use should be taken into consideration. As with residential buildings, the necessary input data are gathered to determine the energy performances of the building, and a calculation of the yearly energy requirements for heating and consumable hot water is performed on the basis of the gathered data, in accordance with [9]. Energy costs can be analysed for non residential buildings, and energy consumption can be modelled according to need, in particular:

— electricity costs and consumption characteristics,
— thermal energy costs and consumption characteristics,
— costs of water for sanitary use and consumption characteristics.

Cost analysis is optimally performed for the period of three years, or 36 months.

It is often necessary to perform additional measurements to precisely determine the existing energy performance of a building and all the technical systems in the building. When there is reasonable doubt in the accuracy of input data needed to calculate the energy performance of the external envelope and the technical systems, the following measurements can be implemented:

— measuring thermal losses through the external envelope (figures 2 and 4) using infrared thermography (IRT), and measuring airtightness (Blower Door Test), measuring thermal resistance,
— in air conditioning, heating, cooling and ventilation systems,
— electrical power parameters of electricity consumption – per energy-using device or subsystem.

Slika 2 — ICT snimka napravljene prilikom energetskog pregleda u svrhu vizualizacije toplinskih mostova i nehomogenosti vanjskog zida, karakteristični katovi bez toplinske zaštite, EIHP, 2008.
Figure 2 — IRT image made during an energy audit with the purpose of visualising thermal bridges and inhomogeneity of the outer wall, characteristic floors without heat retention, EIHP, 2008.

Slika 3 — ICT snimka napravljene prilikom energetskog pregleda u svrhu vizualizacije toplinskih mostova i nehomogenosti vanjskog zida, spoj prizemnog dijela zgrade s terenom, EIHP, 2008.
Figure 3 — IRT image made during an energy audit with the purpose of visualising thermal bridges and inhomogeneity of the outer wall, the connection of the ground part of the building with the terrain, EIHP, 2008.

Osnovni elementi energetskog pregleda postojećih zgrada za potrebe energetskog certificiranja su:

— analiza energetskih svojstava zgrade i karakteristika upravljanja potrošnjom i troškovima energije,
— analiza i izbor mogućih mjera poboljšanja energetskih svojstava zgrade,
— energetsko, ekonomsko i ekološko vrjednovanje predloženih mjera,
— završno izvješće o energetskom pregledu s preporukama i redoslijedom prioritetnih mjera.

Osnovni elementi energetskog pregleda novih zgrada za potrebe energetskog certificiranja su:

— analiza energetskih svojstava zgrade i karakteristika upravljanja potrošnjom i troškovima energije – prema podacima iz

The basic elements of an energy audit of existing buildings for the purpose of energy certification are:

— the analysis of energy performances of the building and the characteristics of consumption and energy costs management,
— the analysis and selection of possible measures for the improvement of the energy performance of the building,
— energy, economic and environmental valuation of proposed measures,
— the final report on the energy audit containing recommendations and the sequence of priority measures.

The basic elements of an energy audit of new buildings for the purpose of energy certification are:

— the analysis of energy performances of the building and the characteristics of energy consumption and costs management – according to the data

projektne dokumentacije i uvidom u izvedeno stanje,
— završno izvješće o energetskom pregledu s iskazom podataka za izradu energetskog certifikata.

Energetskim pregledom se za potrebe energetskog certificiranja analiziraju svi tehnički sustavi zgrade, a računaju se godišnja potrebna toplinska energija za grijanje Q_{Hnd} i godišnja potrebna toplinska energija za zagrijavanje potrošene tople vode Q_W za stvarne klimatske uvjete te se za sada obvezno unose u energetski certifikat, dok je unos ostalih energetskih potreba opcionalan. U konačnosti, energetski certifikat bi trebao sadržavati podatke o ukupnoj primarnoj energiji E_{prim}, kWh/a, odnosno podatke o računski određenoj količini energije za potrebe zgrade tijekom jedne godine, koja obuhvaća ukupnu primarnu energiju za grijanje, pripremu potrošne tople vode, hlađenje i rasvjetu, te energiju za pomoćne uređaje i regulaciju. Uz to trebaju biti iskazane i CO_2 emisije prema utrošku pojedinog izvora energije.

Analiza mogućih mjera poboljšanja energetskih svojstava i povećanja energetske učinkovitosti obvezno uključuje:

— poboljšanje toplinskih karakteristika vanjske ovojnice,
— poboljšanje energetskih svojstava sustava grijanja prostora,
— poboljšanje energetskih svojstava sustava hlađenja prostora,
— poboljšanje energetskih svojstava sustava ventilacije i klimatizacije,
— poboljšanje energetskih svojstava sustava pripreme potrošne tople vode,
— poboljšanje energetskih svojstava sustava potrošnje električne energije – rasvjeta, uređaji i ostala trošila,
— poboljšanje energetskih svojstava specifičnih podsustava,
— analiza mogućnosti zamjene energenta ili korištenja obnovljivih izvora energije za
— proizvodnju toplinske i/ili električne energije,
— poboljšanje sustava regulacije i upravljanja,
— poboljšanje sustava opskrbe vodom i potrošnje (opcionalno),
— potrebne procjene i izračuni ušteda za odabrane mjere.

Mogućnosti poboljšanja energetskih svojstava zgrade možemo podijeliti u dvije skupine:

— mjere uz male troškove i brzi povrat investicije, prema prilogu 4 Pravilnika [6],

from the project documentation and insight into the derived condition,
— the final report on the energy audit with the information presented for the compilation of the energy certificate.

The energy audit, for the needs of energy certification, analyses all the technical systems of a building. The yearly thermal energy required for heating $Q_{H,nd}$ and the yearly thermal energy required for consumable hot water preparation Q_W are calculated for real climate conditions and now must be entered into the energy certificate, while the input of other energy requirements is optional. In its final version, the energy certificate should contain information on total primary energy E_{prim}, kWh/a, or information on the calculated quantity of energy for the requirements of the building during one year, which encompasses the total primary energy for heating, consumable hot water preparation, cooling and lighting, and the energy for auxiliary appliances and regulation. The CO_2 emissions should also be displayed in accordance with the consumption of an individual energy source.

The analysis of possible energy performance improvement measures and the increase of energy efficiency must include:

— the improvement of thermal characteristics of the external envelope,
— the improvement of energy performance of the space heating system,
— the improvement of energy performance of the space cooling system,
— the improvement of energy performance of the ventilation and air condition systems,
— the improvement of energy performance of the consumable hot water preparation system,
— the improvement of energy performance of the electricity consumption system – lighting, appliances and other energy-using devices,
— the improvement of energy performance of specific subsystems,
— the analysis of the possibilities for the substitution of energy sources or the usage of renewable energy sources for the production of thermal energy and/or electricity,
— the improvement of the regulation and management systems,
— the improvement of the water supply and consumption systems (optional),
— the necessary evaluations and calculations of savings for the chosen measures.

The possibilities for the improvement of energy performances of a building can be divided into two groups:

— the measures with small expenses and a quick return of the investment, in accordance with Annex 4 of the Ordinance [6],

— mjere uz veće troškove i dulji povrat investicije, prema prilogu 4 Pravilnika [6].

Radi postizanja veće energetske učinkovitosti potrebno je evaluirati mogućnosti korištenja različitih vrsta izvora energije s gledišta investicije, ušteda i zaštite okoliša. Provedena
analiza svake predložene mjere mora dati sljedeće odgovore:

— koje su godišnje uštede energije i smanjenje emisije ugljičnog dioksida (HRK, kWh, t CO_2),
— koliki su investicijski troškovi, troškovi projektiranja, troškovi montaže i demontaže,
— troškovi puštanja u pogon, vijek trajanja i potrebne dozvole (procjene),
— koliki je period povrata investicije,
— specifikaciju opreme i radova,
— održavanje.

Analiza mjera obvezno se provodi pri energetskim pregledima postojećih zgrada svih vrsta i namjena.

Pri provedbi energetskog pregleda posebno je važno završno izvješće o rezultatima provedenog energetskog pregleda. Završno izvješće sadrži sve prethodno navedene elemente energetskog pregleda i specifikaciju potrebnih podataka za izradu energetskog certifikata zgrade. Također, izvješće može služiti kao podloga za poslovno odlučivanje ključnim ljudima. Energetski certifikat se izrađuje u skladu sa završnim izvješćem. U završnom izvješću, uz sve prikupljene podatke o energetskim svojstvima zgrade, potrebno je specificirati sljedeće podatke:

3.1 Podaci koji se unose u završno izvješće o energetskom pregledu

3.1.1 Opći podaci o zgradi

vrsta zgrade prema namjeni (prema podjeli iz članka 5. stavka 2. PECZ, NN 113/2008)
— lokacija zgrade (katastarska čestica, ulica, kućni broj, mjesto s poštanskim brojem)
— ime i prezime vlasnika, odnosno investitora zgrade
— naziv izvođača radova
— godina završetka izgradnje

3.1.2 Podaci o zgradi

— ploština korisne površine zgrade A_{K_3}, m^2,
— opseg grijanog dijela zgrade V_e, m^3,
— faktor oblika f_0, m^{-1}.
— koeficijent transmisijskog toplinskog gubitka (po jedinici oplošja grijanog dijela zgrade) H'_T, W/(m^{2}K).

— the measures with larger expenses and a longer return of the investment, in accordance with Annex 4 of the Ordinance [6].

To achieve greater energy efficiency it is necessary to evaluate the possibilities of usage of different kinds of energy sources from the viewpoint of the investment, savings and environment protection. The analysis implemented for each proposed measure must yield the following answers:

— what are the yearly energy savings and the reduction of carbon dioxide emissions (HRK, kWh, t CO_2),
— what are the investment costs, engineering costs, assembling and dismantling costs,
— the start of operations costs, lifespan and necessary permits (evaluations),
— what is the period for the return of investments,
— specification of equipment and works,
— maintenance.

The analysis of measures must be performed with the energy audits of existing buildings of all types and uses.

When performing an energy audit, the final report on the results of the performed energy audit is of special importance. The final report contains all the previously stated elements of the energy audit and the specifications of necessary data for the compilation of the energy certificate of a building. Moreover, the report can serve as the basis for executive decisions by key people. The energy certificate is complied in accordance with the final report. In the final report, along with all the gathered data on the energy performances of the building, it is also necessary to specify the following pieces of information:

3.1 Information entered in the final report on the energy audit

3.1.1 General information on the building

type of building according to use (in accordance with the classification from Article 5, Paragraph 2 of the Ordinance on Energy Certification of Buildings, Official Gazette of the Republic of Croatia 113/2008),
— the location of the building (cadastral plot, street, house number, town and postal code),
— name and surname of the building's owner or investor,
— name of the contractor,
— end of construction year.

3.1.2 Information on the building

— surface of the useful area of the building A_{K_3}, m^2,
— volume of the heated part of the building V_e, m^3,
— form factor f_0, m^{-1}.
— transmission heat loss coefficient (per surface unit of the heated part of the building) H'_T, W/(m^{2}K).

3.1.3 Klimatski podaci

- broj stupanj dana grijanja SD, Kd/a,
- broj dana sezone grijanja Z, d,
- srednja vanjska temperatura u sezoni grijanja θ_e, °C,
- unutarnja projektna temperatura u sezoni grijanja θ_i, °C.

3.1.4 Podaci o tehničkim sustavima zgrade

- način grijanja i pripreme potrošne tople vode (lokalno, etažno, centralno, daljinski izvor),
- izvori energije koji se koriste za grijanje,
- izvori energije koji se koriste za pripremu potrošne tople vode,
- način hlađenja (lokalno, etažno, centralno, daljinski izvor),
- izvori energije koji se koriste za hlađenje,
- vrsta ventilacije (prirodna, prisilna bez povrata topline, prisilna s povratom topline),
- vrsta i namjena korištenja sustava s obnovljivim izvorima energije,
- udio obnovljivih izvora energije u potrebnoj toplinskoj energiji za grijanje u postocima.

3.1.5 Podaci o potrebnoj energiji

- godišnja potrebna toplinska energija za grijanje Q_H, kWh/a, kWh/(m²a) i najveća dopuštena vrijednost,
- godišnji toplinski gubici sustava grijanja Q_{Hls}, kWh/a, kWh/(m²a),
- godišnja potrebna toplinska energija za zagrijavanje potrošne tople vode, Q_W, kWh/a, kWh/(m²a),
- godišnji toplinski gubici sustava za zagrijavanje potrošne tople vode Q_{Wls}, kWh/a, kWh/(m²a),
- godišnja potrebna toplinska energija za hlađenje Q_C, kWh/a, kWh/(m²a),
- godišnji gubici sustava hlađenja Q_{Cls}, kWh/a, kWh/(m²a),
- godišnja potrebna energija za ventilaciju u sustavu prisilne ventilacije, djelomične klimatizacije i klimatizacije za stvarne klimatske podatke za definirani profil korištenja Q_{Ve}, kWh/a, kWh/(m²a),
- godišnja potrebna energija za rasvjetu za stvarne klimatske podatke za definirani profil korištenja E_l, kWh/a, kWh/(m²a),
- godišnja isporučena energija E_{del}, kWh/a, kWh/(m²a),
- godišnja primarna energija E_{prim}, kWh/a, kWh/(m²a),
- godišnja emisija CO_2 za stvarne klimatske podatke, kg/a, kg/(m²a),

3.1.6 Koeficijenti prolaska topline za pojedine građevne dijelove zgrade

Građevni dio:

- stvarni U_{stv}, W/(m²K),
- maksimalni U_{max}, W/(m²K).

3.1.3 Climate data

- the number of heating degree days SD, Kd/a,
- the number of heating season days Z, d,
- the mid external temperature during the heating season θ_e, °C,
- the projected internal temperature during the heating season θ_i, °C,

3.1.4 Data on the technical systems of the building

- method for heating and preparation of consumable hot water (local, by floor, central, remote source),
- energy sources used for heating,
- energy sources used for consumable hot water preparation,
- cooling mode (local, by floor, central, remote source),
- energy sources used for cooling,
- ventilation type (natural, forced without heat return, forced with heat return),
- type of renewable energy source systems usage, and their purpose,
- share of renewable energy sources in thermal energy necessary for heating purposes, %.

3.1.5 Data on energy requirements

- yearly thermal energy requirements for heating purposes Q_H, kWh/a, kWh/(m²a) and the maximum allowed value,
- yearly heat losses in heating systems Q_{Hls}, kWh/a, kWh/(m²a),
- yearly thermal energy required for consumable hot water preparation, Q_W, kWh/a, kWh/(m²a)
- yearly heat losses in consumable hot water preparation systems Q_{Wls}, kWh/a, kWh/(m²a),
- yearly thermal energy requirements for cooling Q_C, kWh/a, kWh/(m²a),
- yearly losses in cooling systems Q_{Cls}, kWh/a, kWh/(m²a),
- yearly energy requirements for ventilation in forced ventilation systems, partial air-conditioning and air-conditioning for real climate data for the defined usage profile Q_{Ve}, kWh/a, kWh/(m²a),
- yearly energy requirements for lighting for real climate data for the defined usage profile E_l, kWh/a, kWh/(m²a),
- yearly delivered energy E_{del}, kWh/a, kWh/(m²a),
- yearly primary energy E_{prim}, kWh/a, kWh/(m²a),
- yearly CO_2 emissions for real climate data, kg/a, kg/(m²a).

3.1.6 Heat transfer coefficients for certain structural elements of the building

Structural element:

- U real, W/(m²K),
- U max, W/(m²K).

3.1.7 Redoslijed prioritetnih mjera za poboljšanje energetskih sustava

3.1.7 Order of priority measures for the improvement of energy systems

Tablica 2 – Specifikacija mjera energetskih ušteda u završnom izvješću o energetskom pregledu
Table 2 – Specification of energy-saving measures in the final report on the energy audit

Mjere / Measures	Opis mjere / Measure description	Procjena investicije / Investment estimate (x)	Procijenjene uštede / Estimated savings		Procijenjene uštede / Estimated savings (y)	Jednostavan period povrata / Simple return period x/y	Smanjenje emisije / Emission reduction CO_2
		HRK	kWh/a	Energent / Energy source	HRK/a	Godina / Year	t/a
1							
2							
3							
4							
5							
6							
Ukupno / Total							

4 PROGRAM IZOBRAZBE STRUČNJAKA I OVLAŠTENJA ZA PROVOĐENJE ENERGETSKIH PREGLEDA I ENERGETSKU CERTIFIKACIJU ZGRADA

Pravilnikom [7] definirani su uvjeti i mjerila za davanje ovlaštenja osobama za provođenje energetskih pregleda i energetsko certificiranje zgrada. Također su definirani uvjeti i mjerila za davanje suglasnosti institucijama za provođenje Programa izobrazbe za osobe koje provode energetske preglede i energetsko certificiranje zgrada. Prema Pravilniku, osobe koje provode energetske preglede i energetsko certificiranje zgrada moraju imati ovlaštenje Ministarstva zaštite okoliša, prostornog uređenja i graditeljstva. Ovlaštenje se izdaje fizičkoj ili pravnoj osobi za energetske preglede i energetsko certificiranje stambenih i nestambenih zgrada s jednostavnim tehničkim sustavom, te za energetske preglede zgrada sa složenim tehničkim sustavom.

Pri tome je definirano da su zgrade s jednostavnim tehničkim sustavom:

4 EDUCATION PROGRAM FOR EXPERTS, AUTHORISATIONS FOR THE IMPLEMENTATION OF ENERGY AUDITS AND THE ENERGY CERTIFICATION OF BUILDINGS

The Ordinance [7] defines the conditions and measures for the authorisation of persons for the implementation of energy audits and the energy certification of buildings. It also defines the conditions and measures for granting consent to institutions for the implementation of the education program for the persons performing the energy audits and the energy certification of buildings. In accordance with the Ordinance, the persons performing the energy audits and the energy certification of buildings must be authorised by the Ministry of Environmental Protection, Physical Planning and Construction. The authorisation is issued to a natural or legal person for energy audits and the energy certification of residential and non residential buildings with simple technical systems, and for energy audits of buildings with a complex technical system.

Buildings with a simple technical system are defined as being:

— stambene ili nestambene zgrade bez sustava grijanja, hlađenja, ventilacije te s individualnim sustavima pripreme potrošne tople vode,
— zgrade s pojedinačnim i centralnim izvorima topline za grijanje bez posebnih sustava za povrat topline, s razdiobom toplinske energije i s centralnim ili individualnim sustavima za pripremu potrošne tople vode bez korištenja alternativnih sustava te pojedinačnim rashladnim uređajima, sustavima ventilacije bez povrata topline i ograničenjem buke u ventilacijskim sustavima bez dodatne obrade zraka,

Zgrade sa složenim tehničkim sustavom su:

— stambene ili nestambene zgrade s postrojenjima s centralnim izvorima topline za grijanje i/ili hlađenje zgrade, s centralnom pripremom potrošne tople vode, sa sustavima za mjerenje i razdiobu toplinske i rashladne energije, centralnim rashladnim sustavima, sustavima ventilacije i klimatizacije s povratom topline i ograničenjem buke te dodatnom obradom zraka,
— zgrade sa složenim sustavima za grijanje i hlađenje s korištenjem alternativnih sustava opskrbe energijom, centrale za daljinsko zagrijavanje i hlađenje, rashladna postrojenja, ventilacijski uređaji s reguliranim grijanjem i hlađenjem zraka i klima uređaji, uključujući i pripadajuće rashladne uređaje i druge zgrade koje nisu navedene kao jednostavni tehnički sustavi.

Uvjet za dobivanje ovlaštenja je najmanje završen preddiplomski i diplomski sveučilišni studij ili integrirani preddiplomski i diplomski sveučilišni studij kojim se stječe akademski naziv magistar inženjer arhitektonske, građevinske, strojarske ili elektrotehničke struke, odnosno završen specijalistički diplomski studij kojim se stječe stručni naziv specijalist građevinske, strojarske ili elektrotehničke struke, najmanje pet godina radnog iskustva u struci na poslovima projektiranja, stručnog nadzora građenja, održavanja, odnosno ispitivanja građevinskog dijela zgrade vezano na uštedu energije i toplinsku zaštitu, provođenja energetskih pregleda zgrade, ispitivanja funkcije energetskih sustava u zgradi, ili ispitivanja funkcije sustava automatskog reguliranja i upravljanja u zgradi, te uspješno završen Program osposobljavanja.

Ovlaštena osoba može provoditi samostalno sve energetske preglede zgrada s jednostavnim tehničkim sustavima. Za provođenje energetskih pregleda zgrada sa složenim tehničkim sustavima preporuča se oformiti tim stručnjaka od najmanje tri stručne osobe, pri čemu osoba strojarske struke vrši energetski pregled strojarskog dijela tehničkog sustava zgrade, osoba elektrotehničke

— residential or non residential buildings without heating, cooling or ventilation systems, and with individual consumable hot water preparation systems,
— buildings with individual and central thermal sources for heating without special heat return systems, with a division of thermal energy and central or individual consumable hot water preparation systems without the usage of alternative systems and individual cooling devices, ventilation systems without heat return and noise limitation in ventilation systems without additional air processing,

Buildings with a complex technical system are:

— residential or non residential buildings containing plants with central thermal sources for heating and/or cooling of the building, central consumable hot water preparation systems, systems for the measurement and division of heating and cooling energy, central cooling systems, ventilation and air conditioning systems with heat returns, noise limitation and additional air processing,
— buildings with complex heating and cooling systems using alternative energy supply systems, remote heating and cooling plants, cooling plants, ventilation devices with regulated air heating and cooling and air conditioning devices, including the pertaining cooling devices, and other buildings not listed as simple technical systems.

The conditions for obtaining the authorisation are: completed undergraduate and graduate university studies or integrated undergraduate and graduate university studies with which one obtains the Master in Engineering title in architecture, construction, engineering or electrical engineering, or completed specialist graduate studies with which one obtains the title of a construction, engineering or electrical engineering specialist, at least five years of work experience in the chosen vocation in the areas of engineering, expert supervision of construction, maintenance, testing the structural parts of buildings in connection with energy savings and heat retention, performing energy audits of buildings, testing the functions of energy systems of buildings, testing the functions of automatic regulation and control systems of buildings, and a successfully completed Training Program.

An authorised person can independently perform all energy audits of buildings with simple technical systems. For the implementation of energy audits of buildings with complex technical systems it is recommended to form a professional team of at least three experts where the engineer performs the energy audit of the engineering part of the technical system of the building, the electrical en-struke vrši energetski pregled elektrotehničkog dijela tehničkog sustava zgrade, a osoba arhitektonske ili građevinske struke vrši energetski pregled u dijelu koji se odnosi na građevinske karakteristike zgrade u smislu racionalne uporabe energije i toplinske zaštite. Za provođenje energetskih pregleda i energetsku certifikaciju zgrada može se ovlastiti i pravna osoba koja ima zaposlene stručne kvalificirane osobe odgovarajućih struka. Ovlaštene osobe dužne su se redovito usavršavati.

Stručno osposobljavanje i obvezno usavršavanje osoba koje provode energetske preglede i/ili energetsko certificiranje zgrada provode sveučilišta, veleučilišta, instituti, strukovne organizacije koji imaju suglasnost Ministarstva zaštite okoliša, prostornog uređenja i graditeljstva za obavljanje tih poslova. Trenutačna situacija u rujnu 2009. je ukupno pet ovlaštenih institucija, koje pripremaju prve tečajeve prema Programu izobrazbe definiranom u pravilniku [7]. Program izobrazbe za stručno osposobljavanje i obvezno usavršavanje osoba koje provode energetske preglede i energetsko certificiranje zgrada sastoji se od Modula 1 i Modula 2, te periodičkog stručnog usavršavanja.

Modul 1 obvezno pohađaju:

- fizičke osobe koje se ovlašćuju za provođenje energetskih pregleda i energetsko certificiranje zgrada s jednostavnim tehničkim sustavom,
- osobe zaposlene u pravnoj osobi koja se ovlašćuje za provođenje energetskih pregleda i/ili energetsko certificiranje zgrada s jednostavnim tehničkim sustavom koje provode energetske preglede i energetsko certificiranje zgrada,
- osobe koje u svojstvu imenovane osobe u ovlaštenoj pravnoj osobi potpisuju izvješća o energetskim pregledima i energetske certifikate zgrada s jednostavnim tehničkim sustavom.

Modul 2 obvezno pohađaju:

- fizičke osobe koje se ovlašćuju za provođenje energetskih pregleda zgrada sa složenim tehničkim sustavom,
- osobe zaposlene u pravnoj osobi koja se ovlašćuje za provođenje energetskih pregleda i/ili energetsko certificiranje zgrada sa složenim tehničkim sustavom, koje provode energetske preglede i energetsko certificiranje zgrada,
- osobe koje u svojstvu imenovane osobe u ovlaštenoj pravnoj osobi potpisuju izvješća o energetskim pregledima i energetske certifikate zgrada sa složenim tehničkim sustavom.

gineer performs the energy audit of the electrical engineering part of the technical system of the building, and the architecture or construction expert performs the energy audit in the part related to the construction characteristics of the building in the sense of rational energy use and heat retention. A legal person who employs experts qualified in the pertaining professions can also be authorised for the implementation of energy audits and the energy certification of buildings. The authorised persons are required to regularly participate in professional improvement programs.

Vocational training and the required professional improvement programs for persons implementing energy audits and/or energy certification of buildings are undertaken by universities, polytechnics, institutes and vocational organisations approved by the Ministry of Environmental Protection, Physical Planning and Construction. The current situation in September 2009 is five authorised institutions preparing their first courses in accordance with the Education Program defined in the Ordinance [7]. The Education Program for vocational training and the required professional improvement program for persons implementing energy audits and energy certification of buildings are comprised of Module 1 and Module 2 with recurrent professional improvement.

Module 1 must be attended by:

- natural persons authorised for the implementation of energy audits and the energy certification of buildings with a simple technical system,
- persons implementing energy audits and the energy certification of buildings employed by a legal person authorised for the implementation of energy audits and/or energy certification of buildings with a simple technical system,
- persons who, acting as appointed persons with the authorised legal person, sign reports on energy audits and the energy certification of buildings with a simple technical system.

Module 2 must be attended by:

- natural persons authorised for the implementation of energy audits of buildings with a complex technical system,
- persons implementing energy audits and the energy certification of buildings employed by a legal person authorised for the implementation of energy audits and/or energy certification of buildings with a complex technical system,
- persons who, acting as appointed persons with the authorised legal person, sign reports on energy audits and the energy certification of buildings with a complex technical system.

Program osposobljavanja utvrđen u Modulu 2 mogu pohađati samo osobe koje su uspješno završile Program osposobljavanja utvrđen u Modulu 1.

Ovlaštene osobe nakon uspješno završenog Programa osposobljavanja moraju:

— razumjeti ključne postavke i ciljeve direktive [1],
— imati osnovna znanja o drugim izvorima europskog prava koji se odnose na energetsku učinkovitost zgrada,
— dobro poznavati važeće propise kojima se implementira direktiva [1],
— biti sposobne za samostalno prikupljanje podataka o zgradi potrebnih za energetsku ocjenu prema metodologiji propisanoj posebnim propisom,
— primjenjivati računalne programe namijenjene za provođenje potrebnih proračuna radi dobivanja podataka koji se iskazuju kod provedenog energetskog pregleda i energetskog certificiranja zgrade,
— ocijeniti građevinske karakteristike zgrade u smislu racionalnog korištenja energije i toplinske zaštite,
— ocijeniti tehničke sustave zgrade:
— sustav ventilacije,
— sustav za grijanje, hlađenje,
— sustav za pripremu potrošne tople vode,
— sustav rasvjete,
— sustav za automatsku regulaciju i upravljanje,
— interpretirati podatke o zgradi, naročito u odnosu na dimenzije i tip građevnih dijelova zgrade,
— izvesti potrebne proračune vezane uz podatke potrebne za provođenje energetskog pregleda i energetsko certificiranje zgrade,
— dati preporuke za poboljšanje energetskih svojstava zgrade,
— izraditi energetski certifikat zgrade.

Broj potrebnih ovlaštenih osoba za provođenje energetskih pregleda i energetsko certificiranje zgrada ovisi o stambenom i nestambenom fondu zgrada kao i o brzini uvođenja certifikacije. U Akcijskom planu [2] procijenjen je broj od minimalno 500 potrebnih stručnih osoba za provedbu energetske certifikacije zgrada. To je u skladu i s procjenom EU da je potrebno minimalno 100 stručnjaka na milijun stanovnika za kvalitetnu provedbu energetske certifikacije zgrada.

The Training Program determined in Module 2 can only be attended by persons who have successfully completed the Training Program determined in Module 1.

After successful completion of the Training Program, authorised persons must:

— understand the key postulates and goals of the directive [1],
— have the basic knowledge of other sources of european law pertaining to energy efficiency of buildings,
— be well acquainted with the valid regulations which implement the directive [1],
— be capable to independently gather data on the building necessary for the energy evaluation in accordance with the methodology prescribed by special regulations,
— apply computer programs intended for performing necessary calculations to gain data presented in an implemented energy audit and energy certification of a building,
— evaluate construction characteristics of a building in the sense of rational energy use and heat retention,
— evaluate the technical systems of a building:
— the ventilation system,
— the heating and cooling systems,
— the consumable hot water preparation system,
— the lighting system,
— the automatic regulation and management system,
— interpret the data on the building, especially in relation to the dimensions and the type of structural elements of a building,
— derive necessary calculations in relation to data required for the implementation of the energy audit and energy certification of a building,
— give recommendations for the improvements of energy performances of a building,
— compile the energy certificate of a building.

The number of authorised persons needed for the implementation of energy audits and energy certification of buildings depends on the residential and non residential building fund and on the rate of certificate introduction. The Action Plan [2] estimates that a minimum of 500 experts are needed for the implementation of energy certification of buildings. That is also in accordance with the EU estimate that a minimum of 100 experts are required per million inhabitants for a quality implementation of energy certification of buildings.

5 INTEGRACIJA ALTERNATIVNIH SUSTAVA ZA OPSKRBU ENERGIJOM U ZGRADE

Implementacija direktive EPBD [1] donosi i obvezu razmatranja suvremenog energetskog koncepta zgrada, te primjene alternativnih sustava za opskrbu energijom u novim i postojećim zgradama. U Hrvatskoj je ta obveza implementirana kroz tehnički propis [4], članak 52, gdje se navodi:

za zgrade s ploštinom korisne površine veće od 1 000 m² zahtjevu za izdavanje građevinske dozvole, odnosno potvrdi glavnog projekta obvezno se prilaže Elaborat tehničke, ekološke i ekonomske izvedivosti alternativnih sustava za opskrbu energijom, naročito decentraliziranih sustava opskrbe energijom korištenjem obnovljivih izvora energije, kogeneracijskih sustava, daljinskog/blokovskog grijanja, sustava s dizalicama topline te sustava s gorivnim ćelijama.

Ovaj se elaborat obvezno prilaže uz glavni projekt šest mjeseci nakon objave Studije primjenjivosti alternativnih sustava za opskrbu energijom kod novih i postojećih zgrada [10] na službenim internetskim stranicama Ministarstva zaštite okoliša, prostornog uređenja i graditeljstva.

Takvo suvremeno razmatranje energetskog koncepta zgrada vodi razvoju integralnog procesa projektiranja i nužnosti uske suradnje svih projektanata na razmatranju energetskog koncepta zgrade od samog početka projektiranja. Ovakav pristup projektiranju i gradnji vodi konstantnom poboljšanju i unaprjeđenju graditeljstva, povećava kvalitetu korištenih energetskih izvora te potiče korištenje obnovljivih izvora energije. Također se potiče korištenje novih tehnologija i višefunkcionalnih konstruktivnih elemenata zgrade.

Postupak izrade Elaborata [10] započinje određivanjem toplinskog opterećenja zgrade tj. izračunom potrebne toplinske energije za grijanje i hlađenje za odabrano arhitektonsko i građevinsko rješenje i to kod standardne vanjske i unutarnje temperature (slika 4). Za zgradu se zatim definiraju tehnički sustavi (grijanje, hlađenje, ventilacija, priprema tople vode i rasvjeta) te eventualni dodatni parametri energetske potrošnje. Pri tome se analiziraju varijante u kojima se koriste alternativni sustavi. Ukoliko predviđene varijante zahtijevaju izmjene u arhitektonskom i/ili građevinskom rješenju iste se provode u suradnji s nosiocima arhitektonskog i /ili građevinskog rješenja i za novo rješenje se ponavlja proračun toplinskog opterećenja. Na temelju vršnih opterećenja određuju se nazivne snage uređaja termotehničkih sustava, odnosno vrši se izbor opreme.

5 INTEGRATION OF ALTERNATIVE SYSTEMS FOR THE ENERGY SUPPLY OF BUILDINGS

The implementation of the EPBD Directive [1] also imposes the obligation to consider the modern energy concept of buildings, and the application of alternative systems for the energy supply of new and existing buildings. In Croatia that obligation was implemented through the technical regulations [4], Article 52, where it is stated that:

for buildings with the useful area surface larger than 1 000 m², the request for the issuing of the building permit, or the validation of the main project, must be enclosed with a study of technical, environmental and economic feasibility of alternative energy supply systems, particularly decentralised energy supply systems using renewable energy sources, cogeneration systems, remote/block heating, heat pump systems and fuel cells systems.

This study must be enclosed with the main project six months after the publication of the Feasibility Study of Alternative Energy Supply Systems of New and Existing Buildings [10] on the official web site of the Ministry of Environmental Protection, Physical Planning and Construction.

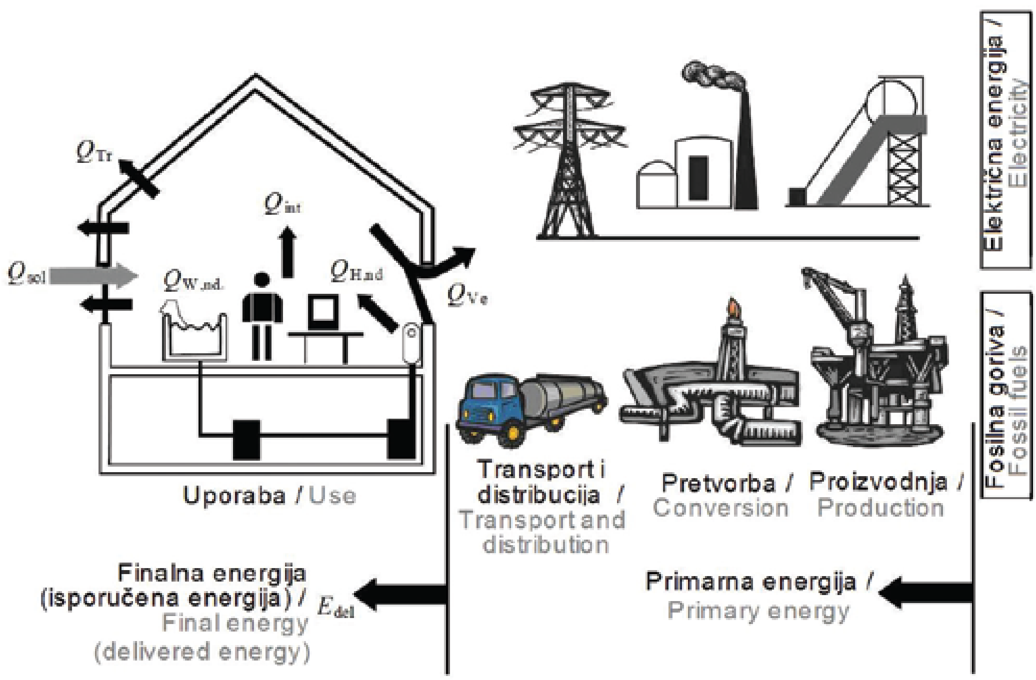
Such a modern consideration of the energy concept of buildings leads towards the development of an integral design process and the necessity for close cooperation of all the engineers on considering the energy concept of a building from the very start of the design process. Such an approach to engineering and construction leads towards a continuous improvement and advancement of construction, increases the quality of the energy sources used and encourages the usage of renewable energy sources. It also encourages the usage of new technologies and multifunctional constructive elements of buildings.

The process of the compilation of the Study [10] begins with the determination of the thermal load of a building, i.e. the calculations of the thermal energy required for heating and cooling of the chosen architectural and construction solution with the standard external and internal temperature (figure 4). The definitions of the technical systems of the building follow (heating, cooling, ventilation, hot water preparation and lighting) together with the possible additional energy consumption parameters. Varieties which use alternative systems are analysed thereat. If the predicted varieties demand changes in the architectural and/or construction solution, they are implemented in cooperation with the holder of the architectural and/or construction solution, and the thermal load calculation is repeated for the new solution. The nominal power of thermotechnical sy-

Za svaki se pojedini sustav potom određuju potrebna toplinska energija za grijanje, klimatizaciju, ventilaciju i hlađenje za stvarne klimatske podatke po mjesecima, zatim toplinska energija za pripremu potrošne tople vode, gubici samih izvora topline i gubici transporta medija nosioca topline te potrebna električna energija za rad pomoćnih uređaja termotehničkih sustava. Elementi termotehničkih sustava grupiraju se prema izvoru energije (plin, električna energija, tekuće gorivo, kruto gorivo) te se određuje ukupna potrebna isporučena energija po energentu i skupno. Koristeći faktore primarne energije određuje se potrebna godišnja primarna energija za zgradu (slika 5), koeficijent utroška sustava i emisija CO_2. Na osnovi izabranih komponenata termotehničkih sustava radi se ekonomska analiza investicijskih troškova te jednostavni period povrata investicije.

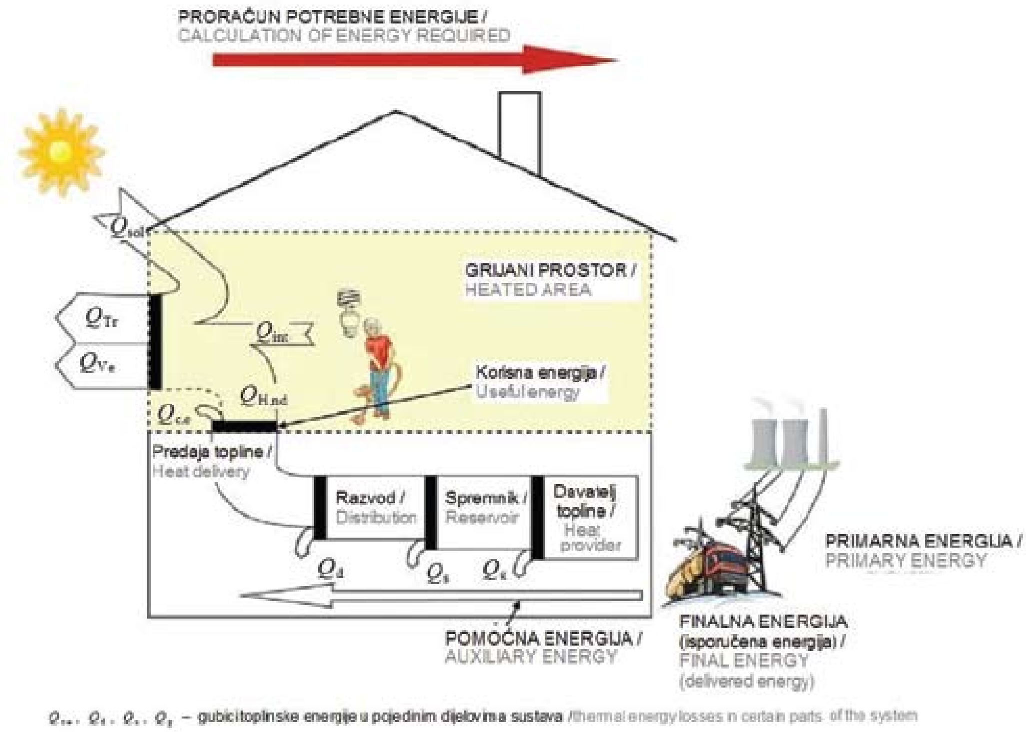
stem devices, or equipment selection, is determined on the basis of peak loads.

The required thermal energy for heating, air-conditioning, ventilation and cooling for real climate data by month, the thermal energy required for consumable hot water preparation, losses of heat sources themselves, transport losses of the heat conducting medium and the electricity required for the functioning of auxiliary devices of thermotechnical systems are then determined for each individual system. The thermotechnical system elements are grouped by energy source (gas, electricity, liquid fuel, solid fuel) and the total required delivered energy is determined per energy source and in total. The required yearly primary energy for the building (figure 5), the system consumption coefficient and CO_2 emissions are determined using the primary energy factors. The economic analysis of investment costs and the simple period for the return of investments is made on the basis of the chosen thermotechnical system components.



Slika 4 — Isporučena energija E_{del} i primarna energija E_{prim} za zgradu [10]

Figure 4 — Delivered energy E_{del} and primary energy E_{prim} for the building [10]



Slika 5 — Energetski tok kroz zgradu s termotehničkim sustavom za grijanje [10]
Figure 5 — Energy flow through a building with a thermotechnical heating system [10]

6 SUVREMENI ENERGETSKI KONCEPTI I INTEGRALNI PRISTUP PROJEKTIRANJU

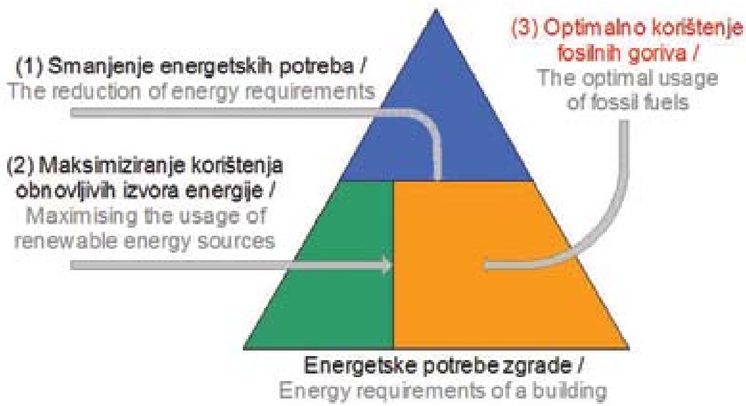
Energetski koncept je integralno i optimalno rješenje u smislu opskrbe energijom i potrošnje energije u projektiranim građevinama. Koncepcija cjelovitog ili integralnog energetski učinkovitog projektiranja podrazumijeva istodobno razmatranje svih aspekata građevine, od arhitekture, pročelja i funkcije, preko konstrukcije, protupožarne zaštite, akustike, pa do potrošnje energije i ekološke kvalitete zgrade, te gospodarenje otpadom. Osnovne metode integralnog projektiranja energetski učinkovite zgrade (slika 6) uključuju tri bitna elementa:

— smanjenje potreba za energijom (energetske uštede),
— maksimiziranje korištenja obnovljivih izvora energije te
— korištenje fosilnih goriva na optimalan način u pogledu zaštite okoliša.

6 MODERN ENERGY CONCEPTS AND AN INTEGRAL APPROACH TO DESIGN

An energy concept is an integral and optimal solution in the sense of energy supply and energy consumption in engineered buildings. The concept of complete or integral energy efficient engineering implies the contemporaneous consideration of all aspects of the building, from architecture, facade and function, through construction, fire protection, acoustics, to energy consumption, environmental quality of the building and waste management. The basic methods of integral design of an energy-efficient building (figure 6) include three key elements:

— reduction of energy requirements (energy savings),
— maximising the usage of renewable energy sources, and
— optimal usage of fossil fuels in view of environment protection.



Slika 6 — Osnovni elementi integralnog projektiranja energetski učinkovite zgrade, prema IEA ECBCS Annex 44, Integrating Environmentally Responsive Elements in Buildings [11]
Figure 6 — The basic elements of integral engineering of an energy efficient building, in accordance with IEA ECBCS Annex 44, Integrating Environmentally Responsive Elements in Buildings [11]

U razmatranje energetskog koncepta treba uključiti [12]:

— kvalitetnu analizu lokacije, orijentacije i oblika zgrada,
— primjenu visokog nivoa toplinske zaštite cijele vanjske ovojnice,
— izbjegavanje toplinskih mostova,
— iskorištavanje toplinskog dobitka od sunca i zaštita od pretjeranog osunčanja,
— korištenje energetski učinkovitih sustava klimatizacije, grijanja, hlađenja i ventilacije (KGHV), te suvremenih alternativnih sustava za opskrbu zgrade energijom,
— korištenje energije iz obnovljivih izvora energije,
— korištenje višefunkcionalnih konstruktivnih elemenata zgrade s integriranim sustavima za proizvodnju energije.

Integralni pristup projektiranju definira se kao pristup koji sve bitne arhitektonske i građevne elemente te sve energetske sustave zgrade povezuje u jedan sustav kako bi se postigle optimalne karakteristike u smislu energetske učinkovitosti, ekološkog utjecaja i unutarnje kvalitete i standarda. Integralno planiranje temelji se na [13]:

— cjelovitom pristupu i integriranju tehničkih, energetskih, ekonomskih, ekoloških i društvenih parametara,
— visokom nivou komunikacije između članova projektnog tima,
— dugoročnom pristupu analizi zgrade, uzimajući u obzir cijeli životni vijek zgrade, uključivo grad-

The following needs to be included in the consideration of the energy concept [12]:

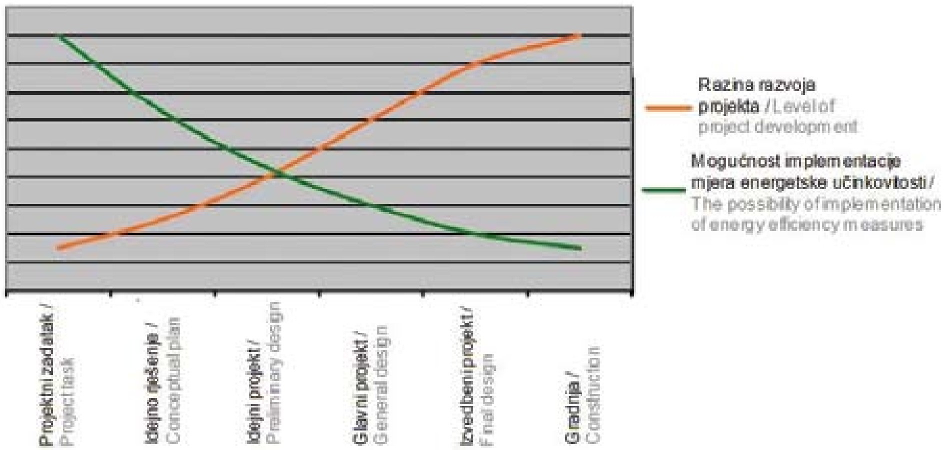
— a quality analysis of the location, orientation and shape of the building,
— the application of a high level of heat retention for the entire external envelope,
— the avoidance of thermal bridges,
— the usage of solar thermal gains and protection against excessive exposure to the sun
— the usage of energy efficient air-conditioning, heating, cooling and ventilation systems (HVAC), and modern alternative energy supply systems for the building,
— the usage of energy from renewable energy sources,
— the usage of multifunctional constructive elements of the building with integrated energy production systems.

The integral approach to design is defined as an approach which connects all relevant architectural and construction elements and all energy systems of a building into one system, in order to achieve optimal characteristics in the sense of energy efficiency, environmental impact, internal quality and standards. Integral planning is based on [13]:

— an integral approach and the integration of technical, energy, economic, environmental and social parameters,
— a high level of communication among the members of the engineering team,
— a long term approach to building analysis, taking into consideration the entire lifespan of a building, including construction, usage, maintenance, reconstruction and demolition.

nju, korištenje, održavanje, obnovu i rušenje. Integralno planiranje je najučinkovitije ako je započeto u ranoj fazi projektiranja (slika 7). Ukoliko se održive tehnologije počnu primjenjivati u kasnijoj fazi projektiranja, rezultat će biti skromna integracija mjera koje će vjerojatno biti preskupe za implementaciju [14].

Integral planning is most effective if started in an early design phase (figure 7). If the application of sustainable technologies begins in a later engineering phase, it will result in a modest integration of measures which will probably be too expensive to implement [14].



Slika 7 — Mogućnost implementacije mjera energetske učinkovitosti i suvremenog energetskog koncepta u odnosu na nivo razvoja projekta

Figure 7 — The possibility of implementation of energy efficiency measures and a modern energy concept in relation to the level of project development

Za integralni pristup projektiranju zgrade potrebno je u fazi idejnog rješenja (kod novih zgrada) odnosno kod planiranja zahvata za rekonstrukciju (kod postojećih zgrada) odrediti karakteristike građevinskih i energetskih sustava zgrade i analizirati potencijal uštede energije, odnosno definirati jedinstveni energetski koncept koji je dio projektnog zadatka. Energetski koncept treba biti podloga za određivanje razine potrošnje svih vrsta energije, vrste korištenih energenata i energetskih sustava. Svako ulaganje u primjenu energetski učinkovitih tehnologija, obnovljive izvore energije i mjere za povećanje toplinske zaštite zgrada potrebno je izraziti kroz energetske, ekološke i ekonomske doprinose. Analizom svih elemenata zgrade moguće je smanjiti potrebe za energijom, odrediti optimalne karakteristike vanjske ovojnice i energetskih sustava. Na taj način se osim troškova za izvedbu zgrade planiraju i troškovi za energiju i održavanje koji imaju značajnu ulogu u ukupnoj vrijednosti zgrade kroz cijelo razdoblje korištenja.

Moguće smjernice pri osmišljavanju suvremenog energetskog koncepta [15] su, npr.:

— u projektiranju je potrebno poštivati principe niskoenergetske arhitekture,

For an integral approach to building design it is necessary to determine the characteristics of the construction and energy systems of a building, analyse the energy saving potential, and define a unique energy concept as a part of the project task in the conceptual plan phase (with new buildings), or when planning reconstruction interventions (with existing buildings). The energy concept should be the basis for determining the consumption levels of all energy types, types of energy sources used and energy systems. Each investment in the application of energy efficient technologies, renewable energy sources and measures for the increase of heat retention of buildings needs to be expressed through energy, environmental and economic contributions. With the analysis of all the elements of a building it is possible to reduce energy requirements, determine optimal characteristics of the external envelope and the energy systems. In such a manner the energy and maintenance costs, which have a significant role in the total value of the building throughout its usage period, are planned in addition to the construction costs.

Possible guidelines for the creation of a modern energy concept [15] are, for example:

— it is necessary to respect the principles of low-energy architecture in the designs,

- toplinska zaštita zgrada treba biti takva da u energetskom certifikatu koji će se izraditi nakon izgradnje, a prije uporabne dozvole, zgrade budu klasificirane u A razred $Q_{Hndref} \leq 25$ kWh/(m²a),
- sustav grijanja, hlađenja, ventilacije i klimatizacije treba centralizirati i dati prijedlog rješenja koje će u konačnosti rezultirati najmanjom energetskom potrošnjom uz prihvatljive financijske pokazatelje,
- potrebno je razmotriti mogućnost proizvodnje energije iz obnovljivih izvora energije s posebnim naglaskom na korištenju Sunčeve energije - integracija elemenata za korištenje obnovljivih izvora energije u arhitekturu,
- visoki nivo toplinske zaštite cijele vanjske ovojnice,
- rješavanje detalja potencijalnih toplinskih mostova,
- kontrola toplinskog zračenja od Sunca kako bi se smanjile potrebe za rashladnom energijom,
- maksimalan ulazak dnevnog osvjetljenja kako bi se smanjila potreba za električnom energijom,
- korištenje prirodnog zasjenjenja gdje je to moguće,
- integralno planirati rješenja svih tehničkih sustava zgrade, kako bi se omogućila centralizacija, visoka energetska učinkovitost, te jednostavno upravljanje potrošnjom za svakog korisnika.

6 ZAKLJUČAK

Energetska certifikacija zgrada, kvalitetno provedena i implementirana, mogla bi odigrati ključnu ulogu u podizanju kvalitete gradnje i kvalitetnom osmišljavanju energetskog kocepta novih zgrada, pokretanju sustavne obnove i osuvremenjivanja postojećeg sektora zgrada, te značajno doprinijeti razvoju integralnog projektiranja, uzimajući u obzir cijeli životni vijek zgrade [16] .

Ključni faktori kojima se projektanti trebaju posvetiti su: integracija alternativnih sustava i obnovljivih izvora energije u arhitekturu i urbanizam, rješavanje višefunkcionalnih konstruktivnih elemenata zgrada, integralno projektiranje i inovativne tehnologije, uz poznavanje financijskih mogućnosti i rizika te unaprjeđenje kvalitete života u zgradama uz smanjenje njihovog ekološkog otiska. Pri tome je posebno važna edukacija i interdisciplinarno razmatranje zgrade kao kompleksnog sustava.

Dobro planiran energetski koncept ima veliki potencijal u smislu održivosti i povećanja energetske učinkovitosti. Najbolji rezultati postižu se integralnim planiranjem poboljšanja standarda, povećanja

- heat retention of buildings must be such that the buildings are classified in the A class $Q_{H,nd,ref} \leq 25$ kWh/(m²a) in the energy certificate compiled after construction, and prior to the issuing of the building inspection certificate,
- the heating, cooling, ventilation and air-conditioning system must be centralised, and a proposal for a final solution, which will result with the smallest possible energy consumption with acceptable financial indicators, must be given,
- it is necessary to consider the possibility of energy production from renewable energy sources with special emphasis on solar energy use – the integration of elements for the use of renewable energy sources into architecture,
- a high level of heat retention for the entire external envelope,
- resolving details of potential thermal bridges,
- controlling solar thermal radiation to reduce requirements for cooling energy,
- maximum entry of daylight to reduce electricity requirements,
- usage of natural shade wherever possible,
- integral planning of solutions for all the technical systems of the building, in order to enable centralisation, high energy efficiency and simple consumption management for each user.

7 CONCLUSION

Energy certification of buildings, if performed and implemented in a quality manner, could play a key role in raising the level of quality in construction, creating a quality energy concept of new buildings, launching a systematic reconstruction and modernisation of the existing building sector, and it could significantly contribute to the development of integral design, taking into consideration the entire lifespan of a building [16].

The key factors the designers should consider are: the integration of alternative systems and renewable energy sources into architecture and urban planning, resolving multifunctional constructive elements of buildings, integral design and innovative technologies, with the awareness of financial options and risks, and the improvement of the quality of living in buildings while reducing their environmental footprint. In that respect, education and interdisciplinary consideration of a building as a complex system is especially important.

A well planned energy concept has great potential in the sense of sustainability and the increase of energy efficiency. The best results can be achieved when integrally planning the improvement of standards, the increase in flexibility, reduction of energy fleksibilnosti, smanjenja potrošnje energije, a time i troškova održavanja, te povećanja korištenja više-funkcionalnih elemenata i obnovljivih izvora energije.

consumption (and consequently maintenance costs), and increased usage of multifunctional elements and renewable energy sources.

LITERATURA / REFERENCES

[1] Direktiva 2002/91/EC o energetskim svojstvima zgrada / Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings (Official Journal L 001, 04/01/2003)

[2] Akcijski plan za implementaciju EPBD u hrvatsko zakonodavstvo, Vlada Republike Hrvatske, ožujak/travanj 2008.

[3] Zakon o prostornom uređenju i gradnji, Narodne novine 76/2007 i 38/2009

[4] Tehnički propis o racionalnoj uporabi energije i toplinskoj zaštiti zgrada Narodne novine 110/2008 i Tehnički propis o izmjeni Tehničkog propisa o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama Narodne novine 89/2009

[5] Tehnički propis o sustavima grijanja i hlađenja zgrada Narodne novine 110/2008

[6] Pravilnik o energetskom certificiranju zgrada Narodne novine 113/2008 i Pravilnik o izmjenama Pravilnika o energetskom certificiranju zgrada Narodne novine 91/2009

[7] Pravilnik o uvjetima i mjerilima za osobe koje provode energetske preglede i energetsko certificiranje zgrada Narodne novine 113/2008 i Pravilnik o izmjenama i dopunama Pravilnika o uvjetima i mjerilima za osobe koje provode energetske preglede i energetsko certificiranje zgrada Narodne novine 89/2009

[8] Metodologija provođenja energetskog pregleda zgrada, Energetski institut Hrvoje Požar, MZOPUG, lipanj 2009.

[9] HRN EN 13790:2008 – Energetska svojstva zgrada – Proračun potrebne energije za grijanje i hlađenje prostora (ISO 13790:2008, EN ISO 13790:2008)

[10] Prijedlog Studije primjenjivosti alternativnih sustava za opskrbu energijom kod novih i postojećih zgrada, Energetski institut Hrvoje Požar, 2009.

[11] IEA ECBCS Annex 44, Integrating Environmentally Responsive Elements in Buildings

[12] HRS BORKOVIĆ, Ž. et al.,Energetska učinkovitost u zgradarstvu – Vodič za sudionike u projektiranju, gradnji, rekonstrukciji i održavanju zgrada, Energetski institut Hrvoje Požar / HEP Toplinarstvo Zagreb, 2007.

[13] REY, F.J., VELASCO, E., VARELA, F. (2007), Building Energy Analyses (BEA): A methodology to assess building energy labelling, Energy and Buildings 39 (2007), 709-716

[14] VUK, B. (et.al.), Energija u Hrvatskoj: godišnji energetski pregled 2007, Zagreb, MINGORP, Energetski institut Hrvoje Požar, 2008.

[15] EnR, Implementation of the EU Energy Performance of Buildings Directive – a snapshot report – EnR lessons learned and recommendation for the future, 2008

[16] CASALS, X.G.(2006) Analysis of Building Energy Regulation and Certification in Europe: Their Role, Limitations and Differences, Energy and Buildings 38, 2006, 381-392

Adrese autora:

Željka Hrs Borković, dipl.ing.arh.
zhrs@eihp.hr
Energetski institut Hrvoje Požar
Savska 163
10000 Zagreb
Hrvatska

Authors' Adresses:

Željka Hrs Borković, dipl. ing.
zhrs@eihp.hr
Energy Institute Hrvoje Požar
Savska 163
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2009-09-01

Prihvaćeno:
2009-09-28

Manuscript received on:
2009-09-01

Accepted on:
2009-09-28

POTROŠNJA ENERGIJE ELEKTRIČNE ŽELJEZNICE

ELECTRIC RAILWAY POWER CONSUMPTION

Milivoj Mandić – Ivo Uglešić – Viktor Milardić, Zagreb, Hrvatska

Električne željeznice predstavljaju specifičnog potrošača elektroenergetskog sustava. Radi racionalnog korištenja električne energije i odgovarajućih ušteda nastoji se optimirati potrošnja energije električnih vlakova i ostalih postrojenja električne željeznice. U radu je prikazan algoritam za simulaciju kretanja vlakova kojim se određuje najprije mehanička, a potom i električna snaga potrebna za vuču. Dionice elektrificirane pruge se napajaju iz elektrovučne podstanice (EVP), a za potrebe elektrovučnog proračuna formira se električna mreža. Na osnovi maksimalnog voznog reda za određeni vremenski period provodi se proračun električnih prilika; struja, napona, električnih snaga, kao i ukupno utrošene energije. Za određivanje potrošnje energije vučnog vozila treba izračunati otpore kretanja pojedinog vlaka na svakoj dionici. Ulazni podaci nužni za takav proračun su parametri profila pruge, planirane brzine kretanja na pojedinim dionicama, te karakteristike vlaka i lokomotive. Uz model za simulaciju kretanja vlaka u članku je prikazana analiza utjecajnih faktora na potrošnju električne energije za elektromotorni vlak, koji prometuje na hrvatskim prigradskim željeznicama. Rezultati su dobiveni algoritmom za simulaciju kretanja vlaka pomoću kojeg se izračunavaju položaji vlakova, kao i njihove mehaničke i električne snage potrebne za vuču. Na konkretnom primjeru napajanja postojećeg EVP-a su uspoređeni rezultati dobiveni elektrovučnim proračunom i mjerenjem. Dani su neki od rezultata elektrovučnog proračuna za EVP Zaprešić pri napajanju prigradske pruge Podsused Tv. – Samobor – Bregana, koja se planira izgraditi.

The electric railways is a specific consumer of the electric power system. For the purpose of using electric energy rationally and making adequate savings, efforts are made to optimize electric energy consumption of electric trains and other electric railway facilities. The work shows the train movement simulation algorithm which serves to determine primarily the mechanical and then also the electric power required for traction. The sections of the electrified tracks are supplied from the electric traction substation (TS) and, for the requirements of the electric traction calculation, an electric network is formed. Based on the maximum time table for a certain time period, calculation is done of the electric circumstances; electricity, voltage, electric power, as well as the total consumed electric energy. For the determination of the electric energy supply of the traction unit, movement resistances of the certain train on each section need to be calculated. Input data necessary for such a calculation are the tracks profile parameters, planned movement speeds on certain sections, and the properties of the train and the locomotive. Besides the train movement simulation model, the article also shows the analysis of impact factors on the electric energy consumption for the electromotor train which travels the Croatian suburban rails. The results are obtained by the train movement simulation algorithm, by virtue of which the locations of trains are calculated, as well as their mechanical and electric powers necessary for traction. The particular example of the supply of the existing SS serves for comparing the results obtained by electric traction calculation and measurement. Some of the results are given of the electric traction simulation for the Zaprešić SS at the supply of the suburban Podsused factory – Samobor – Bregana which is planned for construction

Ključne riječi: elektromotorni vlak; EVP; elektrovučni proračun; koeficijent adhezije; potrošnja električne energije; rekuperacija; simulator kretanja vlaka
Key words: adhesion coefficient; electric energy consumption; electric traction calculation; electromotor train; TS; recuperation; train movement simulator

1 UVOD

Optimalnom potrošnjom energije električnih vlakova nastoje se ostvariti uštede i racionalizacija sveukupnog poslovanja uz uvjet efikasnog i pravovremenog prometa vlakova. Radi kontinuiranog trenda rasta cijene električne energije, problemi ekonomičnog i pouzdanog korištenja električne vuče postaju sve veći izazov za korisnike i proizvođače električnih željeznica.

Glavni pristup uštede energije u željezničkom prometu ovisi o energetski efikasnoj konstrukciji lokomotiva, efikasnom reduciranju otpora pri kretanju vlaka, kao i o odgovarajućem održavanju voznog parka i tračnica [1].

Zbog porasta cijene energije i sve većeg razvoja prigradskog željezničkog prometa, sve više se pozornosti posvećuje racionalnoj potrošnji električne energije prigradskih vlakova. Parametri koji utječu na potrošnju električne energije elektromotornog vlaka su:

- vučne karakteristike elektromotornog vlaka (vučni pasoš),
- kočione karakteristike elektromotornog vlaka,
- faktor snage,
- masa vlaka,
- snaga pomoćnih pogona (rasvjeta, hlađenje motora, grijanje vagona i sl.),
- profil pruge (radijus krivine i nagib),
- maksimalno dozvoljena brzina na određenoj dionici,
- rekuperacija (predviđeno vraćanje snage u kontaktnu mrežu pri kočenju),
- grafikon voznog reda.

Računske simulacije kretanja vlakova predstavljaju efikasno i ekonomično sredstvo kojim se može odrediti potrošnja energije vlaka, uz određene ulazne parametre. Između ostalog je u nastavku dan matematički model simulacije kretanja vlaka i parametarska analiza utjecajnih faktora na potrošnju energije za elektromotorni vlak koji prometuje prigradskim prugama.

2 MATEMATIČKI MODEL SIMULACIJE KRETANJA VLAKA

Pri kretanju vozila prugom pojavljuju se različiti otpori vožnje koji se protive tom kretanju. Da bi otpori bili svladani, vučno vozilo mora na obodu pogonskih kotača ostvariti vučnu silu jednaku zbroju svih otpora. Otpori vožnje mogu biti stalni i promjenjivi.

1 INTRODUCTION

Electric trains' optimum power consumption is used to achieve savings and rationalization of the total business operation under the condition of efficient and timely railway traffic. For the purpose of a continued trend of rising electric energy prices, the issues of economical and reliable use of electric traction are becoming more and more of a challenge for the users and producers of electric tracks.

The main approach of energy savings in railway traffic depends on the energy-efficient locomotive construction, efficient resistance reduction at train movement as well as on the adequate maintenance of the rolling stock and the tracks [1].

Because of the rise in energy prices and the increasing development of the suburban railway traffic, an increasing amount of attention is given to the suburban trains' electric energy consumption. The parameters which impact electromotor train electric energy consumption are:

- electromotor train traction properties (rolling resistance),
- braking characteristics of the electromotor train,
- power factor,
- train weight,
- auxiliary drive power (lighting, motor cooling, wagon heating, etc.),
- tracks profile (bend radius and slant),
- maximum allowed speed on the certain section,
- recuperation (planned return of power into the contact network at braking),
- time table graph.

Computational train movement simulations represent an efficient and economical means by which the consumption of train's electric energy can be determined with certain input parameters. Inter alia, a mathematical model of train movement simulation is given below, as well as the parameter analysis of impact factors on the electromotor train electric energy consumption which travels the suburban tracks.

2 MATHEMATICAL TRAIN MOVEMENT SIMULATION MODEL

When the vehicles move along the tracks, various drive resistances appear which oppose that movement. In order for the resistances to be handled, the traction vehicle must realize a traction force equal to the sum of all resistances at the edge of the driving wheels. Drive resistances can be constant or variable.

Stalni otpori se pojavljuju uvijek pri kretanju vlaka i za njihovo izračunavanje se koriste iskustveni izrazi koje se mogu razlikovati u različitim zemljama. U modelu koji je predložen u nastavku usvojen je izraz za specifični otpor po Strahl-u [2]. Specifični otpor se dobije svođenjem otpora na jedinicu mase.

Specifični otpori se posebno računaju za vučno vozilo, a posebno za vlak.

Povremeni otpori su otpori koji se pojavljuju ovisno o profilu pruge, a tu spadaju:

— otpori uspona,
— otpori krivine.

U proračunu otpora krivine koriste se eksperimentalne formule u kojima uglavnom egzistira polumjer zavoja kao najutjecajnija veličina pa se za izračunavanje specifičnog otpora krivine u simulaciji kretanja vlaka korišten izraz (1):

Constant resistances always appear when the train moves and their calculation requires empiric expressions which might differ from country to country. The model which is suggested below contains the expression for the specific resistance according to Strahl [2]. The specific resistance is obtained by reducing the resistance to the weight unit.

Specific resistances are calculated separately for the traction vehicle and separately for the train.

Occasional resistances are resistances which appear depending on the tracks profile and these include:

— climb resistances,
— bend resistances.

In the calculation of bend resistances experimental formulas are used in which the turn radius mostly exists as the most influential dimension so that the following expression is used for the calculation of the specific bend resistance in the train movement simulation (1):

$$f_z = \frac{8\ 000}{R} \cdot 10^{-3} \qquad (1)$$

gdje je:

f_Z – specifični otpor u zavoju, N/kg,
R – radijus krivine, m.

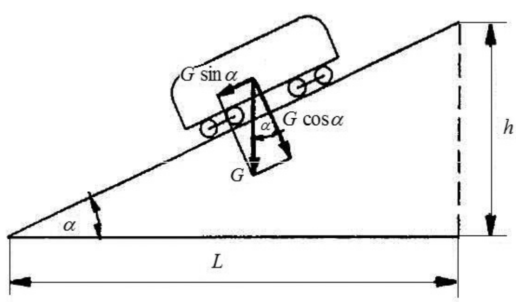
Otpor na usponu, čiji je nagib pod kutom α, se određuje pomoću sile F_i koja je paralelna tračnicama (slika 1), a iznosi:

where it is as follows:

f_Z – specific resistance in the turn, N/kg,
R – bend radius, m.

The resistance at the climb, the slant of which is at the angle α and which is determined by virtue of the force F_i parallel with the tracks (Figure 1) and which amounts to:

$$F_i = \pm G \cdot \sin\alpha, \ \ \mathrm{N} \ . \qquad (1a)$$



Slika 1 — Prikaz sila na usponu
Figure 1 — Overview of the forces at the climb

Taj otpor mora biti svladan da bi se vozilo moglo kretati uz uspon. U slučaju kretanja niz uspon ovaj otpor ima negativan predznak i djeluje kao vučna sila.

Izraz za specifični otpor uspona koji je korišten u algoritmu je dan izrazom (2):

That resistance must be overcome in order for the vehicle to be able to move upward. In case of moving downward, this resistance has a negative prefix and acts as a traction force.

The expression for the specific climb resistance used in the algorithm is given by the expression (2):

$$f_i = \pm \frac{i}{100} \quad , \qquad (2)$$

gdje je:

f_i – specifični otpor na usponu, N/kg,
i – uspon pruge, ‰.

it is as follows:

f_i – specific resistance at the climb, N/kg,
i – tracks climb, ‰.

Otpor ubrzavanja se pojavljuje pri svakoj promjeni brzine, a izraz za specifični otpor ubrzanja koji je korišten u algoritmu je dan izrazom (3):

The acceleration resistance appears at any change of speed, and the expression for the specific acceleration resistance used in the algorithm is given by the expression (3):

$$f_a = (1+\varepsilon)\cdot a \qquad (3)$$

gdje je:

f_a – specifični otpor ubrzanja, N/kg,
ε – koeficijent rotirajućih masa (0,06–0,08),
α – ubrzanje vlaka izraženo, m/s^2.

where it is as follows:

f_a – specific resistance at acceleration, N/kg,
ε – rotating masses coefficient (0,06–0,08),
α – train acceleration expressed, m/s^2.

Nakon određivanja otpora koji se pojavljuju prilikom kretanja pojedinog vlaka potrebno je utvrditi posjeduje li elektrovučno vozilo dovoljnu vučnu silu za svladavanje otpora. Radi toga se provjerava tzv. vučni pasoš električnog vozila, koji po svojoj konturi predstavlja granične mogućnosti vučnog vozila. Grafički se prikazuje kao ovisnost vučne sile o brzini. Vučni pasoš daje osnovno obilježje vučnih mogućnosti i popratni je tehnički dokument svakog vučnog vozila. Pri malim brzinama vučna sila može doseći veoma velike vrijednosti i premašiti silu adhezije te će nastupiti proklizavanje. Da ne bi došlo do proklizavanja pogonskih kotača po tračnicama mora biti ispunjen sljedeći uvjet [3]:

After the determination of the resistances which appear at the movement of a certain train, it is necessary to assess whether the traction vehicle has sufficient traction force for overcoming the resistance. That is why the rolling resistances of the electric vehicle are verified, as its contour represents the borderline possibilities of the traction vehicle. It is graphically depicted as the dependency of the traction force on the speed. The rolling resistance properties provide the basic criterion of traction possibilities and these represent the supporting technical document of each traction vehicle. At small speeds, the traction force may reach very high values and exceed the adhesion force, and then sliding will take place. In order to prevent the driving wheels from sliding on the tracks, the following condition must be met [3]:

$$F_v \le \xi \cdot G_{ad} = F_{ad} \qquad (4)$$

gdje je:

F_v – vučna sila, N,

where it is as follows:

F_v – traction force, N,

$F_{a\,d}$ – sila adhezije, N,
G_{ad} – adheziona težina (težina vučnog vozila), N,
ξ – koeficijent adhezije [4].

Iz izraza (4) se može zaključiti da vučna sila mora biti manja ili jednaka sili adhezije $F_{a\,d}$.
Koeficijent adhezije, osim o stanju tračnica, ovisi i o stanju kotača. Ako je kotač oštećen, osovinski pritisak varira pa se ξ smanjuje. Također postoji njegova ovisnost o brzini prikazana u izrazu (5).

$F_{a\,d}$ – adhesion force, N,
G_{ad} – adhesion weight (traction vehicle weight), N,
ξ – adhesion coefficient [4].

From the expression (4), it can be concluded that the traction force must be lower or equal to the adhesion force $F_{a\,d}$.

Besides the condition of the tracks, the adhesion coefficient also depends on the condition of the wheels. If the wheel is damaged, the axis pressure varies and ξ decreases. There also exists its dependency on the speed shown in expression (5).

$$\xi = \frac{\xi_0}{1+0{,}015 \cdot v} \qquad (5)$$

gdje je:

v – brzina vozila, km/h,
ξ_0 – statički koeficijent adhezije za koji se uzima:
$\xi_0 = 0{,}38$ – za suhe tračnice,
$\xi_0 = 0{,}25$ – za mokre tračnice,
$\xi_0 = 0{,}18$ – za masne tračnice.

Izraz (5) pokazuje da se povećanjem brzine smanjuje koeficijent adhezije. Ograničeni koeficijent adhezije ograničava maksimalnu snagu, maksimalno ubrzanje i maksimalni uspon (odnosno pad) koji se može svladati pa je maksimalna vučna snaga u zavisnosti od brzine v dana izrazom (6):

where it is as follows:

v – vehicle speed, km/h,
ξ_0 – static adhesion coefficient for which it is taken:
$\xi_0 = 0{,}38$ – for dry tracks,
$\xi_0 = 0{,}25$ – for wet tracks,
$\xi_0 = 0{,}18$ – for greasy tracks.

The expression (5) shows that with the increase of the speed, the adhesion coefficient decreases. The limited adhesion coefficient limits the maximum power, maximum acceleration and maximum climb (that is, decline) which can be overcome, so the maximum traction power is dependant on the speed v given by expression (6):

$$P_{v\,max} = F_v \cdot v = \xi \cdot G_{a\,d} \cdot v = \frac{\xi_0}{1+0{,}015 \cdot v} \cdot G_{ad} \cdot v \quad , \qquad (6)$$

Na osnovi izraza (6) se može zaključiti da je $P_{v\,max}$ ograničena zbog adhezije. Ovo znači da u laganu lokomotivu nema smisla ugrađivati motore velike instalirane snage. Zbog male adhezije pri velikim brzinama se ne može iskoristiti sva instalirana snaga vučnog motora.

Vrijednost za maksimalno ubrzanje vlaka dana je izrazom (7) iz [5]:

Based on the expression (6) it can be concluded that $P_{v\,max}$ is limited due to adhesion. This means that it doesn't make sense to install locomotives of great installed power. Due to small adhesion at great speeds, not all the installed power of the traction vehicle can be used.

The value for maximum train acceleration is given by the expression (7) from [5]:

$$a_{max} = \frac{1\,000 \cdot \xi \cdot G_{ad}}{102 \cdot (1+\varepsilon) \cdot (G_{ad} + G_t)} \quad , \qquad (7)$$

gdje je:

G_t – težina tereta, N,
$G_a + G_t$ – ukupna težina elektromotornog vlaka, N.

where it is as follows:

G_t – cargo weight, N,
$G_a + G_t$ – total train electromotor weight, N.

Izraz (7) pokazuje da je maksimalno ubrzanje vlaka proporcionalno težini vučnog vozila, a obrnuto proporcionalno ukupnoj težini vlaka.

Ako uzmemo da ukupna težina elektromotornog vlaka ($G_{ad} + G_t$) iznosi 1 800 N, a težina vučnog vozila (G_{ad}) 670 N dobije se da maksimalno ubrzanje za elektromotorni vlak iznosi oko 1,14 m/s^2.

Isto tako se dobije da maksimalno ubrzanje teretnih vlakova tipično iznosi oko 0,5 m/s^2. Maksimalno ubrzanje je također ograničeno zbog udobnosti putnika, u simulacijama kretanja vlakova se može koristiti ubrzanje od 0,5 m/s^2.

Znajući potrebnu vučnu silu za ostvarenje kretanja vlaka, moguće je izračunati mehaničku snagu na obodu kotača prema izrazu (8):

Expression (7) shows that the maximum train acceleration is proportional to the weight of the traction vehicle and inversely proportional to the train's weight.

If it is taken that the total weight of the electromotor train ($G_{ad} + G_t$) amounts to 1 800 N and that the weight of the traction vehicle (G_{ad}) is 670 N, the result is that the maximum acceleration for the electromotor train amounts to about 1,14 m/s^2.

The result that the acceleration of cargo trains typically amounts to about 0,5 m/s^2 is obtained in the same way. Maximum acceleration is also limited for the purpose of the passengers' comfort; in the simulations of train movement maximum acceleration of 0,5 m/s^2 can be used.

If the traction force necessary for the realization of train movement is known, it is possible to calculate the mechanical force on the wheels' edges according to the expression (8):

$$P_m = F_v \cdot v \qquad (8)$$

gdje je:

P_m – mehanička snaga, W,
F_v – vučna sila, N,
v – brzina, m/s.

Za izračunavanje djelatne snage koju vlak uzima iz mreže potrebno je poznavati faktor korisnosti (η) vučnog vozila koji ovisi o brzini kretanja vlaka i naponu mreže. U slučaju da nije poznata krivulja promjene faktora η može se pretpostaviti neka konstantna vrijednost, npr. 0,8 ili slična. Potrebno je još poznavati snagu pomoćnih pogona vlaka (hlađenje motora, grijanje vagona i sl.). Ta snaga se mijenja po mjesecima [6], a u simulacijama se može uzeti neka konstantna vrijednost snage pomoćnih pogona, npr. 250 kW.

Električna djelatna snaga koju vlak uzima iz mreže može se odrediti prema izrazu (9):

where it is as follows:

P_m – mechanical power, W,
F_v – traction force, N,
v – speed, m/s.

For the calculation of the active power which the train takes from the network, it is necessary to know the efficacy (η) of the traction vehicle which depends on the train movement speed and the network voltage. In case the η factor alteration curve is not known, a certain constant value can be assumed, e.g. 0,8 or similar. It is also necessary to know the power of auxiliary train drives (motor cooling, wagon heating, etc.). That power changes according to month [6] and a certain constant value of the auxiliary drives power can be taken in the simulations, such as 250 kW.

Electric active power the train takes from the network can be determined according to the expression (9):

$$P_{el} = \frac{P_m}{\eta} + P_{pom} \,, \qquad (9)$$

gdje je:

P_{el} – električna djelatna snaga, W,
P_{pom} – snaga pomoćnih pogona, W,
η – faktor korisnosti vučnog vozila.

U slučaju izmjeničnog napajanja pored djelatne snage vlak uzima i jalovu snagu iz mreže. Jalova snaga se računa prema izrazu (10):

where it is as follows:

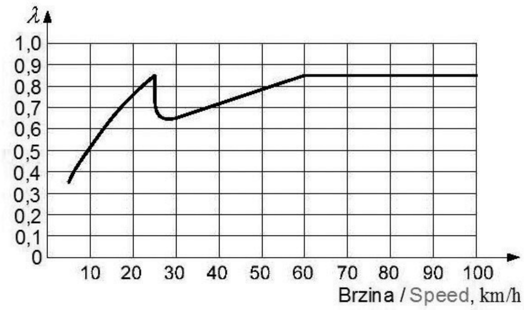
P_{el} – electric active power, W,
P_{pom} – auxiliary drives power, W,
η – traction vehicle efficiency factor.

In case of alternate supply, besides the active power, the train also takes reactive power from the network. Reactive power is calculated according to the expression (10):

$$Q_{el} = P_{el} \cdot \tan[\arccos(\cos \lambda)] \quad (10)$$

Faktor snage λ je ovisan o brzini kretanja vozila, a izgled te krivulje za elektromotorni vlak je prikazan na slici 2. $\cos(\varphi)$ predstavlja faktor snage koji se odnosi samo na osnovni harmonik, dok faktor λ uključuje udjele viših harmonika koji su prisutni u struji vuče.

The power factor is dependant on vehicle movement and the appearance of that curve for the electromotor train is shown in Figure 2. $\cos(\varphi)$ represents the power factor which refers only to the basic harmonic, while factor λ also includes the shares of higher harmonics present in the traction current.



Slika 2 — Krivulja faktora snage λ elektromotornoga vlaka
Figure 2 — Electromotor train power factor curve λ

Poznavanje faktora λ je naročito važno u prometu s čestim pokretanjem i zaustavljanjem jer je pri malim brzinama faktor snage manji.

Moderne lokomotive sadrže u sebi PWM (pulsno širinska modulacija) pretvarače koji stvaraju više harmonike, a oni se zatim šire kontaktnom i prijenosnom mrežom [7].

Na moderna vučna vozila u sustavima električne vuče 25 kV, 50 Hz postavljaju se zahtjevi na smanjenu potrošnju jalove energije i smanjen sadržaj viših harmonika u struji vuče. Potrošnja električne energije vlaka u vremenskom intervalu t se računa prema izrazu (11):

Knowing the λ factor is especially important in traffic with frequent starts and stops because the power factor is lower at smaller speeds.

Contemporary locomotives contain within themselves the pulse-width modulation (PWM) converters which create higher harmonics which then spread through the contact and transmission network [7].

Contemporary traction vehicles in the 25 kV, 50 Hz electric traction systems are subjected to requirements regarding reduced consumption of reactive power and reduced contents of higher harmonics in the traction current. The train's electric energy consumption in the time interval t is calculated according to the expression (11):

$$E = \sum_{i=1}^{n} P \cdot \Delta t \quad (11)$$

gdje je:

- Δt – korak proračuna, s,
- P – djelatna snaga za svaki korak proračuna, MW,
- n – broj iteracija proračuna, $t/\Delta t$.

where it is as follows:

- Δt – calculation step, s,
- P – active power for each calculation step, MW,
- n – number of calculation iterations, $t/\Delta t$.

Iz izraza (10) se vidi da se energija računa numerički za svaki korak proračuna Δt i na kraju se sumira da bi se dobila ukupna potrošnja energije elektromotornog vlaka.

U simulaciji kretanja vlaka je također omogućeno uzimanje u obzir povrat snage u mrežu, tj. rekuperacija prilikom kočenja vlaka. Krivulja elektrodinamičke kočnice elektromotornog vlaka serije HŽ 6111 i formule za izračun snage koja se vraća u mrežu se nalazi u [3]. Faktor korisnosti električne kočnice (η_k) kreće se od 0,66 do 0,85 ovisno o konstrukciji kočnice. U algoritmu je pretpostavljena vrijednost $\eta_k = 0{,}85$. Snagu je moguće vratiti u mrežu u slučaju da vlak pri kretanju koči električnom kočnicom (na većim strminama) ili prilikom zaustavljanja jer u tim slučajevima je $P_m<0$. Snaga kočnice se računa prema sljedećem izrazu (12):

The expression (10) reveals that the power is numerically calculated for each calculation step Δt and it is summed up in the end in order to obtain the electromotor train's total power consumption.

The return of the power into the network, that is, recuperation at train's braking, can also be taken into consideration at train movement simulation. The curve of the electromotor train electrodynamic brake of the HŽ 6111 series and of the formula for the calculation of the power which returns into the network can be found in [3]. The electric brake efficiency factor (η_k) fluctuates from 0,66 to 0,85 depending on the brake structure. The value of $\eta_k = 0{,}85$ is assumed in the algorithm. The power can be returned to the network in case the train, while moving, brakes with the electric brake (on greater precipices) or when stopping because in such cases $P_m<0$. The brake's power is calculated according to the following expression (12):

$$P_{ek} = F_k \cdot v \quad (12)$$

gdje je:

P_{ek} – snaga kočnice, W,
F_k – sila električne kočnice, N,
v – brzina, m/s.

where it is as follows:

P_{ek} – brake's power, W,
F_k – electric brake force, N,
v – speed, m/s.

Budući da prilikom kočenja mehanička snaga na obodu kotača ima negativni predznak, u mrežu je moguće vratiti snagu ovisno o tome da li je apsolutna vrijednost mehaničke snage veća ili manja od snage kočnice pa imamo dva slučaja:

Because the mechanical power on the wheel's edge has a negative prefix upon braking, the power can be returned into the network regardless of whether the absolute value of the mechanical power is greater or lower than the brake's power, so, two cases arise:

Ako je $P_m>P_{ek}$ u mrežu je moguće vratiti snagu:

If $P_m>P_{ek}$ power can be returned into the network:

$$P_e = P_{ek} \cdot \eta_k - P_{pom} \;, \; \mathrm{W} \,, \quad (13)$$

Ako je $P_m<P_{ek}$ u mrežu je moguće vratiti snagu:

If $P_m<P_{ek}$ power can be returned into the network:

$$P_e = |P_m| \cdot \eta_k - P_{pom} \;, \; \mathrm{W} \,. \quad (13)$$

3 SIMULACIJA ELEKTRIČNE VUČE

Napajanje kontaktne mreže 25 kV, 50 Hz iz elektrovučnih podstanica može biti jednostrano (radijalno) ili dvostrano, Na hrvatskim prugama 25 kV, 50 Hz najčešće se koristi jednostrano napajanje.

Ovdje će se prikazati odgovarajući algoritam za elektrovučni proračun, koji je primijenjen za slu-

3 ELECTRIC TRACTION SIMULATION

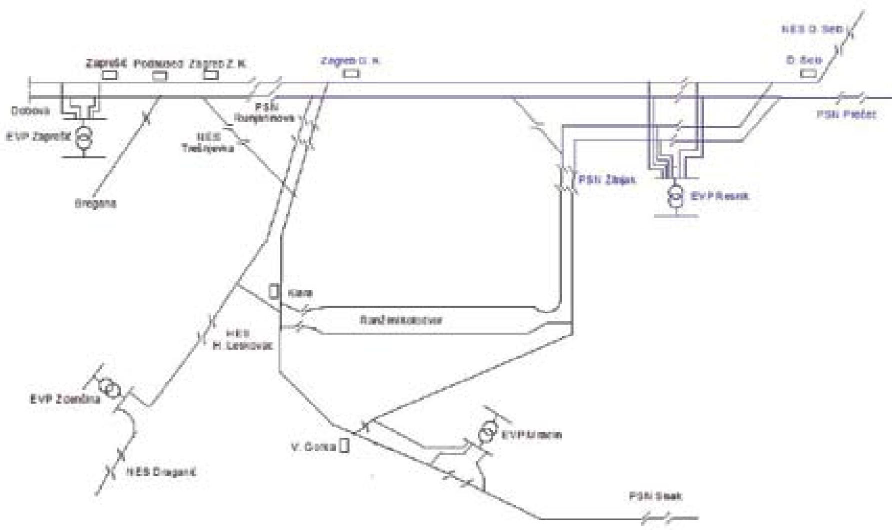
Supplying the 25 kV, 50 Hz-contact network from electric traction substations can be unilateral (radial) or bilateral. On the Croatian 25 kV, 50 Hz-railway tracks, unilateral supply is most often used.

The adequate algorithm for the electric traction calculation, applied in the unilateral supply case, will be čaj jednostranog napajanja. Rezultati dobiveni proračunom usporedit će se s rezultatima mjerenja, koja su provedena u elektrovučnoj podstanici Resnik.

shown here. The results obtained by calculation will be compared with the results of the measurements undertaken at the Resnik electric traction substation.

Shema napajanja željezničkog čvora Zagreb prikazana je slikom 3. Vidljivo je područje redovitog napajanja EVP Resnik (plava linija) kao i područja napajanja susjednih EVP-a.

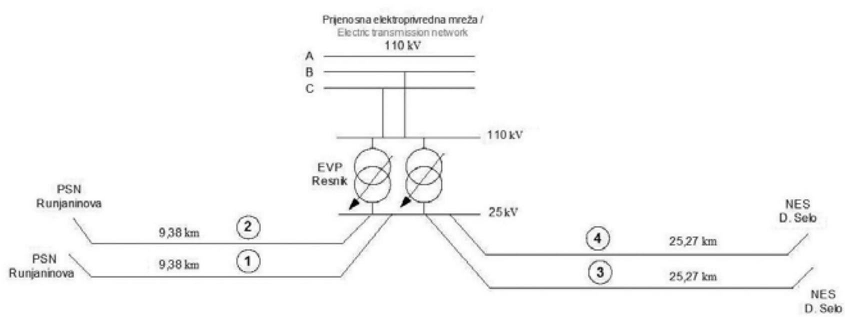
The Zagreb railway knot supply scheme is shown in Figure 3. The area of regular supply of the Resnik electric traction substation (SS) (blue line) is visible, as well of the neighbouring TSs.



Slika 3 — Mreža elektrificiranih pruga na području Zagreba
Figure 3 — The network of electrified tracks in the Zagreb area

Duljine krakova napajanja EVP Resnik u normalnom pogonu su prikazane na slici 4. Napojni vod 1 priključen je na dio kontaktne mreže koja napaja vlakove koji prometuju prema Zagrebu, a napojni vod 2 vlakove prema Sesvetama.

The lengths of supply arms of SS Resnik under normal operation are shown in Figure 4. Feeder current 1 is connected onto the part of the contact network which connects trains travelling towards Zagreb and feeder current 2 onto the part which supplies the trains towards Sesvete.

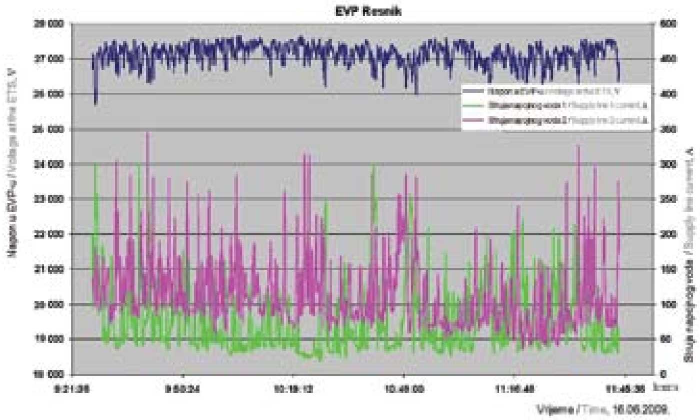


Slika 4 — Duljine krakova napajanja EVP Resnik
Figure 4 — The network of electrified tracks in the Zagreb area

Mjerenja struja i napona na 25 kV strani EVP 25/100 kV Resnik provela su se na sekundarnoj strani, pri čemu su mjerni instrumenti bili priključeni na zaštitnu jezgru strujnog i naponskog transformatora

Measurements of currents and voltages on the 25 kV-side of the 25/100 kV SS Resnik were undertaken on the secondary side, whereat the measurement instruments were connected onto the safety u 25 kV dijelu postrojenja. Rezultati mjerenja su prikazani na slici 5.

core of the current and voltage transformer in the 25 kV-part of the facility. Measurement results are shown in Figure 5.



Slika 5 — Napon i struje u EVP Resnik na 25 kV strani

Figure 5 — Voltage and currents at the Resnik ETS on the 25 kV side

Mjerenja su obavljena 16. lipnja 2009. u vremenskom intervalu od 9:30 do 11:30.
Plava linija prikazuje iznos napona u EVP-u u tom vremenskom periodu, dok crvena i zelena linija prikazuju struje napojnih vodova 1 i 2.

U tablici 1 se nalazi popis vlakova koji su prometovali u tom vremenskom periodu na dionici Zagreb G.K. – D. Selo.

Measurements were undertaken on 16 June 2009 in the time interval from 9:30 to 11:30.
The blue line shows the amount of voltage at the SS in that time period while the red and the green lines show the currents of the feeder currents 1 and 2.

Table 1 shows the list of trains which travelled during that time on the Zagreb G.K. (Main Railway Station) – Dugo Selo section.

Tablica 1- Popis vlakova na dionici Zagreb GK – D. Selo (16.06.2009. od 9:30 do 11:30)
Table 1 – List of trains on the Zagreb GK – D. Selo section (16 June 2009 from 9:30 - 11.30)

Šifra vlaka / Train code	Težina vlaka / Train weight t	Vrijeme polaska / Time of departure h:m	Vrijeme dolaska / Time of arrival h:m	Mjesto polaska / Place of departure	Mjesto dolaska / Place of arrival	Vrsta lokomotive / Locomotive type
8029	176	9:09	9:33	Zagreb GK	D. Selo	6111-023
741	273	9:15	9:35	Zagreb GK	D. Selo	1142-012
8030	176	9:55	10:21	D. Selo	Zagreb GK	6111-023
8031	176	9:25	9:50	Zagreb GK	D. Selo	6111-008
8032	176	10:22	10:47	D. Selo	Zagreb GK	6111-008
2013	134	9:46	10:10	Zagreb GK	D. Selo	1141-306
1751	198	10:03	10:20	Zagreb GK	D. Selo	1142-004
703	203	10:09	10:28	Zagreb GK	D. Selo	1141-004
744	210	10:40	10:59	D. Selo	Zagreb GK	1141-230
2012	135	11:00	11:24	D. Selo	Zagreb GK	1141-015
8034	176	11:08	11:34	D. Selo	Zagreb GK	6111-007
8035	176	10:13	10:39	Zagreb GK	D. Selo	6111-007
38025	82	9:38	9:57	Zagreb GK	D. Selo	462-002
47981	759	11:15	11:39	D. Selo	Zagreb GK	1141-007
45902	1245	10:45	11:08	Zagreb GK	D. Selo	1141-106
415	289	11:04	11:21	Zagreb GK	D. Selo	1142-015
2173	176	10:38	11:04	Zagreb GK	D. Selo	6111-024

U zadnjem stupcu tablice 1 je navedena vrsta lokomotive koja pokreće pojedini vlak. Mogu se uočiti 4 vrste lokomotiva i to:

— 6111 – elektromotorni vlak,
— 1141 – četiriosovinska diodna lokomotiva,
— 1142 – četiriosovinska tiristorska lokomotiva,
— 462 – šestosovinksa diodna lokomotiva.

Vučne karakteristike lokomotiva predstavljaju podatak potreban za proračun, a navedene su u [3].

U nastavku će se prikazati rezultati dobiveni simulacijama za navedeni vozni red. U elektrovučni proračun su uzeti i vlakovi koji prometuju na dionici od Zagreb G.K. – PSN Runjaninova u danom vremenskom intervalu, kako bi se dobilo stvarno stanje reda vožnje.

U prvoj fazi proračuna simulira se kretanje vlaka, a kao rezltat simulacije se dobije za svaki vlak lokacija vlaka (udaljenost od EVP-a), brzina, zatim djelatna i jalova snaga potrebna za napajanje vlaka iz kontaktne mreže. Ovi se podaci privremeno pohranjuju u bazu i kasnije se koriste za druge proračune, pa se tako može na primjer dobiti podatak o vlakovima, koji se istodobno nalaze na pojedinom kraku napajanja EVP-a.

Nakon simulacije kretanja svakog pojedinog vlaka slijedi formiranje električne mreže, koje je specifično iz razloga što se shema napajanja stalno mijenja (neki vlakovi ulaze, a neki izlaze iz područja napajanja).

Nakon formiranja električne mreže slijedi proračun tokova snaga i to se ponavlja za svaki korak proračuna (najčešće 2 sekunde) u promatranom vremenskom periodu simulacije elektrovučnog proračuna.

Rezultati proračuna uspoređeni su s mjerenim rezultatima u kraćim vremenskim peridoima.

Za napojni vod 1 je promatran vremenski interval od 10:40 do 10:45. Prikaz rezultata dobivenih proračunom i mjerenjem za taj vremenski period se nalazi na slici 6.

The last column of Table 1 determines the type of locomotive which drives the certain train. 4 locomotive types are evident, namely:

— 6111 – electromotor train,
— 1141 – four-axis diode locomotive,
— 1142 – four-axis thyristor locomotive,
— 462 – six-axis diode locomotive.

Locomotives' traction properties represent information necessary for the calculation and these are stated in [3].

The results obtained by simulations for the said time schedule will be presented below. The electric traction calculation also included the trains travelling the Zagreb GK – PSN Runjaninova section in the given time interval, so as to obtain the real condition of the time schedule.

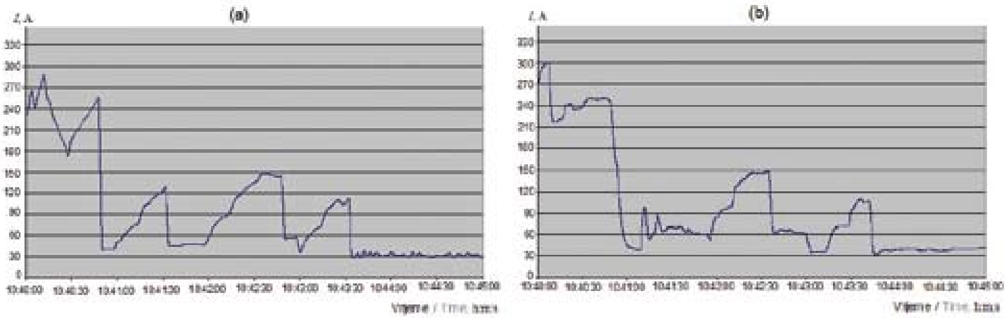
In the first calculation phase, train movement was simulated and as a result of the simulation, train location was obtained for each train (distance from the SS), its speed, active and reactive powers necessary for supplying the train from the contact network. These data are temporarily stored in the database and then used later for other calculations, so that, for example, data can be obtained on trains which are located on a certain SS supply arm at the same time.

After the simulation of the movement of each particular train, the forming of the electric network follows which is specific because the supply scheme changes constantly (some trains enter and some exit the supply area).

After the formation of the electric network, the calculation of current flows follows, and this is repeated for each step of the calculation (most often 2 seconds) in the observed time period of the simulation of the electric traction calculation.

Calculation results are compared with the results of the measurement in shorter periods of time.

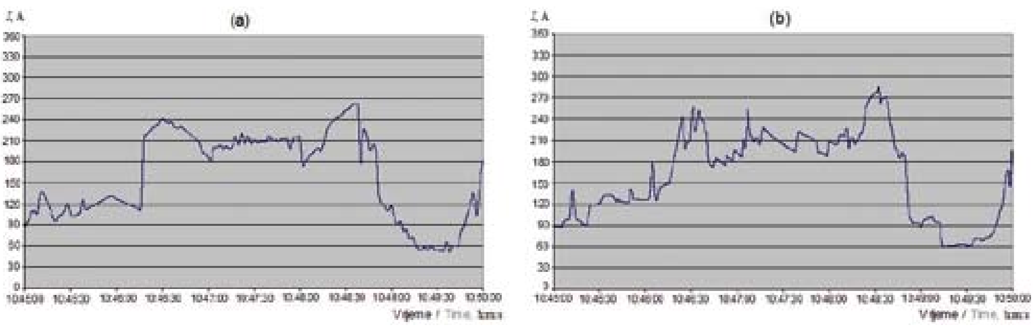
For feeder current 1, the time interval from 10:40 to 10:45 is observed. The overview of the results obtained by the calculation and measurement for that time period can be found in Figure 6.



Slika 6 — Struja napojnog voda 1: a) proračun b) mjerenje
Figure 6 — Supply line 1 current: a) calculation b) measurement

Za napojni krak 2 je promatran vremenski interval od 10:45 do 10:50, kada je prometovao teretni vlak mase 1 245 t i 6 elektromotornih vlakova. Prikaz rezultata dobivenih proračunom i mjerenjem za taj vremenski period se nalazi na slici 7.

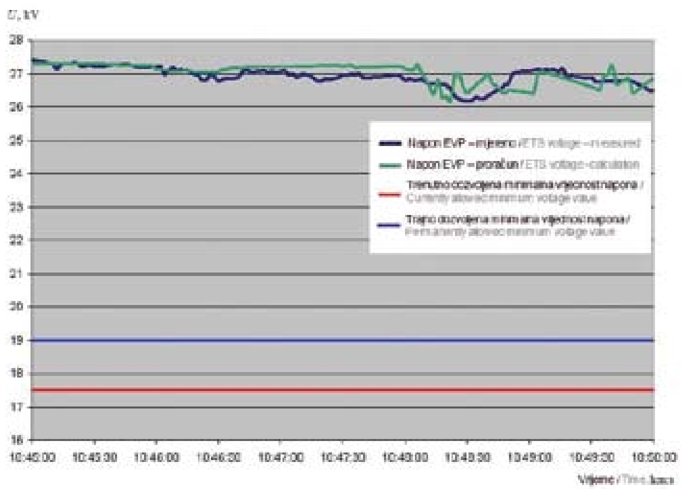
For the feeder current 2, the time interval from 10:45 to 10:50, when the 1 245 t cargo train and 6 electromotor trains travelled, is observed. The overview of the results obtained by calculation and measurement for that time period can be found in Figure 7.



Slika 7 — Struja napojnog voda 2: a) proračun b) mjerenje
Figure 7 — Supply line 2 current: a) calculation b) measurement

U proračunima je potrebno poznavati veliki broj ulaznih parametara, a neki od njih su promjenjivi u vrlo širokim granicama, pa se tako za proračune uzimaju pretpostavljene srednje vrijednosti (kao npr. ubrzavanje). Stvarno izmjerene struje zavise i o načinu upravljanja vučnim vozilom, što se u proračunima isto tako pretpostavlja. Na osnovi navedenih grafičkih prikaza može se zaključiti da se dobiveni rezultati elektrovučnim proračunom relativno dobro slažu s mjerenim rezultatima struje napojnih vodova 1 i 2. Slična podudarnost rezultata dobiva se i kod napona u EVP-u (slika 8).

When performing the calculation, it is necessary to know a large number of input parameters and some of these are variable within very wide limits so that the assumed mean value (such as, for example, acceleration) is taken for the calculations. The actually measured currents also depend on the manner of handling the traction vehicle, and this is also assumed in the calculations. Based on the said graphic presentations, it can be concluded that the results obtained by electric traction calculation agree relatively well with the measurement results of the current of feeder currents 1 and 2. Similar conformance of results is also obtained with the voltage at the SS (Figure 8).



Slika 8 — Napon u EVP Resnik
Figure 8 — Voltage at the Resnik ETS

4 ANALIZA UTJECAJNIH FAKTORA NA POTROŠNJU ELEKTRIČNE ENERGIJE ELEKTROMOTORNOG VLAKA

U ovom poglavlju će se prikazati parametarska analiza nekih utjecajnih faktora na potrošnju električne energije elektromotornog vlaka. Parametri tog vlaka su navedeni u [3], a rezultati su dobiveni algoritmom za simulaciju kretanja vlaka pomoću kojeg se izračunavaju položaji vlakova, kao i njihove mehaničke i električne snage potrebne za vuču [2].

4.1 Radijus krivine

Ulazni podaci potrebni za simulator kretanja vlaka se nalaze u tablici 2.

4 ANALYSIS OF IMPACT FACTORS ON THE ELECTROMOTOR TRAIN ELECTRIC ENERGY CONSUMPTION

In this chapter, the parametric analysis of certain impact factors on the electromotor train electric energy consumption will be presented. That train's parameters are stated in [3], and the results are obtained by the train movement simulation algorithm by virtue of which train locations are calculated, as well as their mechanical and electric powers necessary for traction [2].

4.1 Bend radius

Input data necessary for the train movement simulator can be found in Table 2.

Tablica 2 – Ulazni podaci simulatora kretanja vlaka za parametarsku analizu radijusa krivine
Table 2 – Input data of the train movement simulator for the parametric analysis of the bend radius

Redni broj dionice / Section number	Duljina dionice / Section length, m	Radijus krivine / Bend radius, m	Uspon pruge / Tracks climb, ‰	Planirana brzina / Planned speed, km/h
1.	500	300	0	100
2.	500	500	0	100
3.	500	800	0	100
4.	500	1 500	0	100
5.	500	3 000	0	100
6.	500	5 000	0	100
7.	500	10 000	0	100
8.	500	∞	0	100

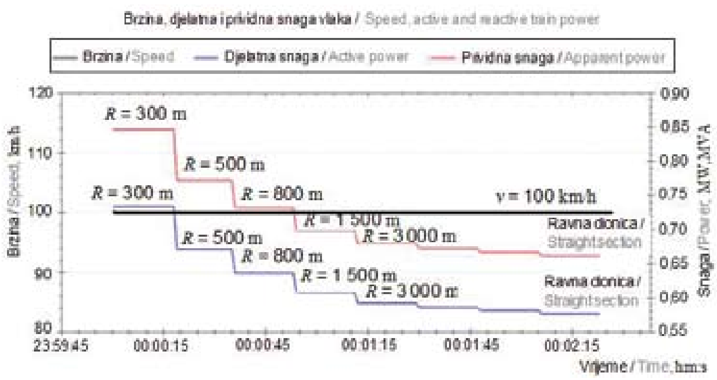
Proračun je proveden za prosječne brzine elektromotornog vlaka (70 km/h do 100 km/h) uz pretpo-

The calculation was undertaken for electromotor train average speeds (70 km/h to 100 km/h) under stavku da elektromotorni vlak cijelo vrijeme vozi planiranom brzinom.

Na slici 9 su prikazani rezultati ovisnosti djelatne i prividne snage o radijusu krivine za ulazne podatke (tablica 2) dobiven pomoću algoritma za simulaciju kretanja vlaka. Vidljivo je da je ta ovisnost zanemariva za velike radijuse krivine.

the assumption that the electromotor train is travelling at the planned speed the entire time.

Figure 9 shows the results of the dependency of the active and apparent power on the bend radius for input data (Table 2) obtained by virtue of the train simulation algorithm. That dependency is evidently insignificant for extensive bend radiuses.



Slika 9 — Ovisnost djelatne i prividne snage o radijusu krivine pri konstantnoj brzini
Figure 9 — Dependency of the active and reactive power on the bend radius at constant speed

Slična ovisnost bi se dobila i za ostale brzine kretanja elektromotornog vlaka. Rezultati simulacije kretanja vlaka (potrošnja električne energije i djelatna električna snaga) za navedene planirane brzine se nalaze u tablici 3. U zadnjem stupcu su dobivene vrijednosti za ravnu dionicu pruge.

Na osnovi dobivenih rezultata se može zaključiti kako nema značajnije promjene u potrošnji energije elektromotornog vlaka za radijuse krivine iznad 5 000 m.

Proračuni pokazuju da razlika u potrošnji energije elektromotornog vlaka, za slučaj kada dionica ima radijus krivine od 300 m u odnosu na slučaj kada je dionica potpuno ravna, za sve brzine iznosi oko 27 %.

Similar dependency would also be obtained for other electromotor train movement speeds. Train movement simulation results (electric energy consumption and active electric power) for the said planned speeds can be found in Table 3. The values obtained for the straight tracks sections can be found in the last column.

Based on the obtained results, it can be concluded that no significant change in the electromotor train consumption occurs for bend radiuses over 5 000 m.

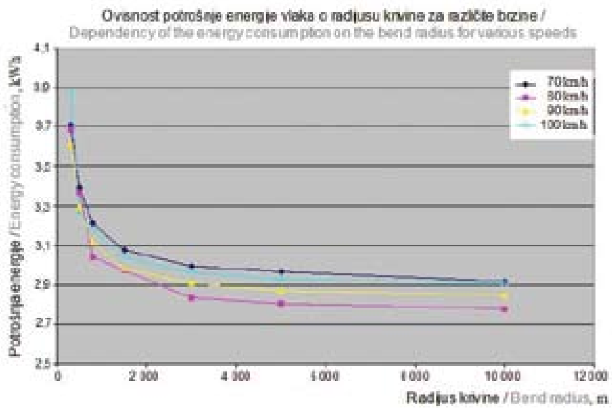
The calculations show that the difference in the electromotor train energy consumption, for the case when the section has a bend radius of 300 in relation to the case when the section is completely straight, amounts to about 27 % for all speeds.

Tablica 3 – Utjecaj različitog radijusa krivine pruge na potrošnju energije elektromotornog vlaka
Table 3 – Impact of different tracks bend radiuses on the electromotor train energy consumption

Brzina vlaka / Train speed, km/h	Radijus krivine / Bend radius, m	300	500	800	1 500	3 000	5 000	10 000	∞
70	E, kWh	3,712	3,394	3,213	3,077	2,997	2,968	2,939	2,918
	P, kWh	0,514	0,470	0,445	0,426	0,415	0,411	0,407	0,404
80	E, kWh	3,686	3,367	3,043	2,975	2,836	2,805	2,781	2,756
	P, kWh	0,577	0,527	0,498	0,476	0,464	0,459	0,455	0,451
90	E, kWh	3,611	3,294	3,117	2,983	2,910	2,872	2,850	2,828
	P, kWh	0,650	0,593	0,561	0,537	0,523	0,517	0,513	0,509
100	E, kWh	3,873	3,262	3,180	3,040	2,965	2,930	2,910	2,724
	P, kWh	0,734	0,671	0,636	0,608	0,593	0,586	0,582	0,577

Prikaz ukupnih rezultata (tablica 3) se nalazi na slici 10 i može se zaključiti da potrošnja energije za pojedini radijus krivine nije proporcionalna brzini (iako je potrebna djelatna snaga proporcionalna brzini, tablica 3). To pokazuje da je optimizacija potrošnje energije vlaka omogućena optimiranjem brzine pojedine dionice [8].

The overview of the overall results (Table 3) can be found in Figure 10 and the conclusion can be drawn that the energy consumption for particular bend radiuses is not proportional to speed (although the necessary active power is proportional to speed, Table 3). That shows that the optimization of the train's energy consumption is enabled by optimizing the speed of the particular section [8].



Slika 10 — Krivulja ovisnosti potrošnje energije elektromotornog vlaka o radijusu krivine
Figure 10 — Curve of the electromotor train energy consumption dependency on the bend radius

4.2 Uspon pruge

U nastavku će se promatrati ovisnost potrošnje energije elektromotornog vlaka o usponu pruge. Ulazni podaci potrebni za simulator kretanja vlaka se nalaze u tablici 4. Budući da se vrijednost maksimalnog uspona za željeznicu kreće do 30 ‰ (proporcionalna adhezionoj težini vozila, a obrnuto proporcionalna ukupnoj težini vozila) za simulaciju su uzete vrijednosti nagiba pruge navedene u četvrtom stupcu tablice 4.

Proračun je proveden, kao u prethodnom slučaju, za prosječne brzine elektromotornog vlaka (70 km/h do 100 km/h), uz pretpostavku da elektromotorni vlak cijelo vrijeme vozi planiranom brzinom.

4.2 Tracks climb

The dependency of the electromotor train energy consumption on the tracks climb will be observed below. The input data necessary for the train movement simulator can be found in Table 4. Because the value of the maximum climb for the railway fluctuates up to 30 ‰ (proportional to the vehicle's adhesion weight and inversely proportionate to the vehicle's total weight), values of the tracks slant stated in the fourth column of Table 4 are taken for the simulation.

The calculation was undertaken, as in the former case, for electromotor train average speeds (70 km/h to 100 km/h) under the assumption that the electromotor train is travelling at the planned speed the entire time.

Tablica 4 – Podaci za parametarsku analizu nagiba pruge
Table 4 – Data for the parametric analysis of the tracks slant

Redni broj dionice / Section number	Duljina dionice / Section length, m	Radijus krivine / Bend radius, m	Uspon pruge / Tracks climb, ‰	Planirana brzina / Planned speed, km/h
1.	500	∞	0	100
2.	500	∞	4	100
3.	500	∞	8	100
4.	500	∞	12	100
5.	500	∞	16	100
6.	500	∞	20	100
7.	500	∞	24	100
8.	500	∞	28	100

Na slici 11 su prikazani rezultati ovisnosti djelatne i prividne snage o radijusu krivine za podatke dane u tablici 4 iz koje je vidljiva linearna ovisnost.

Figure 11 shows the results of the dependency of the active and apparent power on the bend radius for the data given in Table 4, which reveals the linear dependency.

Slika 11 — Ovisnost djelatne i prividne snage o usponu pruge pri konstantnoj brzini
Figure 11 — Dependency of the active and apparent power on the bend radius at constant speed

Slična ovisnost bi se dobila i za ostale brzine kretanja elektromotornog vlaka. Rezultati proračuna potrošnje električne energije i djelatne električne snage za navedene planirane brzine su prikazani u tablici 5.

Similar dependency would also be obtained for other electromotor train movement speeds. Results of the electric energy and active electric power calculation for the stated planned speeds are shown in Table 5.

Tablica 5 – Utjecaj različitog uspona pruge na potrošnju energije elektromotornog vlaka
Table 5 – Impact of different tracks climbs on the electromotor train energy consumption

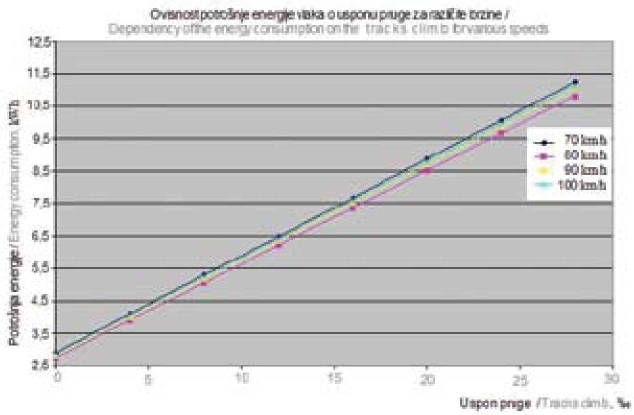
Brzina vlaka / Train speed, km/h	Uspon pruge / Tracks climb, ‰	0	4	8	12	16	20	24	28
70	*E*, kWh	2,918	4,109	5,301	6,486	7,677	8,869	10,053	11,245
	P, kWh	0,404	0,569	0,734	0,898	1,063	1,228	1,392	1,557
80	*E*, kWh	2,756	3,911	5,060	6,209	7,358	8,513	9,662	10,811
	P, kWh	0,451	0.640	0,828	1,016	1,204	1,393	1,581	1,769
90	*E*, kWh	2,828	4,000	5,178	6,356	7,533	8,706	9,883	11,061
	P, kWh	0,509	0,720	0,932	1,144	1,356	1,567	1,779	1,991
100	*E*, kWh	2,885	4,060	5,240	6,415	7,590	8,770	9,945	11,120
	P, kWh	0,577	0,812	1,048	1,283	1,518	1,754	1,989	2,224

Prikaz ukupnih rezultata je dan na slici 12 s koje je vidljivo da potrošnja energije elektromotornog vlaka linearno raste s porastom uspona promatrane dionice pruge.

Sa slike 12 je vidljivo da postoji manja ovisnost potrošnje energije za određeni iznos uspona pruge o trenutačnoj brzini vlaka nego u prethodnom poglavlju (krivulje su gušće raspoređene).

The presentation of the overall results is given in Figure 12 which reveals that electromotor train energy consumption increases linearly with the increase of the climb of the observed tracks section.

Figure 12 reveals that there is less dependency of energy consumption for the certain tracks climb value on the train's momentary speed than in the previous chapter (the curves are more densely arranged).



Slika 12 — Ovisnost potrošnje energije elektromotornog vlaka o usponu pruge
Figure 12 — Dependency of electromotor train energy consumption on the tracks climb

4.3 Rekuperacija

Ako je vučno vozilo predviđeno za rekuperaciju, tada je moguće vratiti dio snage električne kočnice u mrežu. Rekuperacija, odnosno povrat snage u mrežu, može značajno utjecati na uštedu potrošnje energije u prigradskom prometu [9]. Poboljšanom izvedbom kočionih diskova se može uštedjeti značajan iznos električne energije [10]. Iskustva pokazuju da prilikom takvog kočenja prigradska elektrovučna vozila mogu davati u mrežu i do 40 % ukupno preuzete energije. Elektromotorni vlakovi imaju bolje rekuperativne kočione karakteristike od vlakova vučenih lokomotivama, jer je kod njih uključeno više osovina prilikom kočenja. Što je veća snaga elektromotora, te uz veći broj osovina uključenih u kočenje, više energije može biti vraćeno u kontaktnu mrežu. U algoritmu je također modelirana rekuperacija prilikom kočenja vlaka i u nastavku će se na konkretnom primjeru simulacije vlaka razmotriti ušteda energije, ako je rekuperacija omogućena. Ulazni podaci trase za koju je proveden proračun se nalaze u tablici 6. Ukupna duljina trase je 13,5 km.

4.3 Recuperation

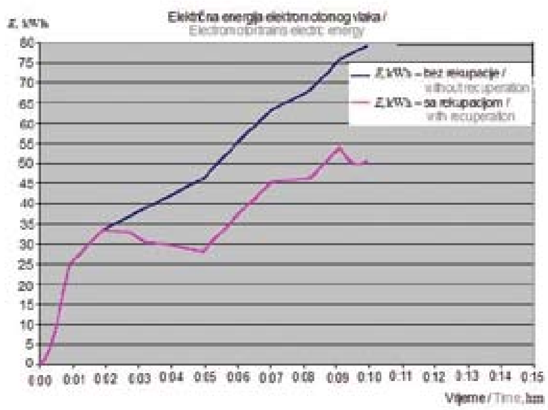
If the traction vehicle is planned for recuperation, then it is possible to return a part of the electric brake's power to the network. Recuperation, that is, return of power into the network, can significantly affect the savings in energy consumption in suburban traffic [9]. Improved performance of brake disks can provide for savings of significant amounts of electric energy [10]. Experience shows that upon such braking, suburban electric traction vehicles can bring even up to 40 % of the total overtaken energy into the network. Electromotor trains have better recuperative brake properties than the trains pulled by locomotives because these include more axes upon braking. The greater the electromotor power, and the greater the number of axes participating in braking, the more energy can be returned into the contact network. The recuperation upon the train braking is also modelled in the algorithm, and energy savings will be analysed on a particular train movement simulation example in the text below, if recuperation is enabled. Input data for the route for which the calculation was undertaken can be found in Table 6. The total route length is 13,5 km.

Tablica 6 – Podaci za proračun kretanja vlaka uz rekuperaciju
Table 6 – Data for the calculation of the train movement with recuperation

Redni broj dionice / Section number	Duljina dionice / Section length, m	Radijus krivine / Bend radius, m	Uspon pruge / Tracks climb, ‰	Planirana brzina / Planned speed, km/h
	1 298	∞	0	90
	955	∞	0	90
	1 180	40 000	–12,5	90
	750	38 000	–19,4	90
	850	38 000	–12,5	90
	1 750	40 000	–14	90
	1 995	40 000	0	90
	1 150	40 000	–1	90
	1 750	40 000	–10	90
	1 995	40 000	0	90

Treba napomenuti da se elektromotorni vlak kreće trasom na kojoj nema nijednog uspona i da je na većem dijelu trase nizbrdica, na kojoj rekuperativno svojstvo vlaka dolazi do izražaja. Usporedba potrošnje energije elektromotornog vlaka sa i bez mogućnosti rekuperacije je prikazana na slici 13 s koje je vidljivo da ušteda utrošene energije zbog rekuperacije iznosi do 40 %. Naravno, ušteda energije zavisi o profilu pruge, smjeru kretanja i učestalosti potrebe za kočenjem elektromotornog vlaka. Rekuperacijom je omogućena ušteda energije i na postojećim trasama pruge, pa se mogućnost rekuperacije može uzeti u obzir prilikom projektiranja vučnog vozila i elektrovučnih podstanica.

It should be said that the electromotor train moves along the route on which no climbs exist and that the largest part of the route is downhill where the train's recuperative property is manifested. The comparison of electromotor train energy consumption with and without the possibility of recuperation is shown in Figure 13, which reveals that the savings in energy due to recuperation amount up to 40 %. Of course, energy savings depend on the tracks profile, movement direction and the frequency of the electromotor train's need for braking. The recuperation provides for energy savings even on the existing railway routes so the possibility of recuperation can be taken into consideration upon engineering the traction vehicle and the electric traction substations.



Slika 13 — Potrošnja energije elektromotornog vlaka za slučajeve sa i bez rekuperacije
Figure 13 — Electromotor train energy consumption for the cases with and without recuperation

4.4 Brzina

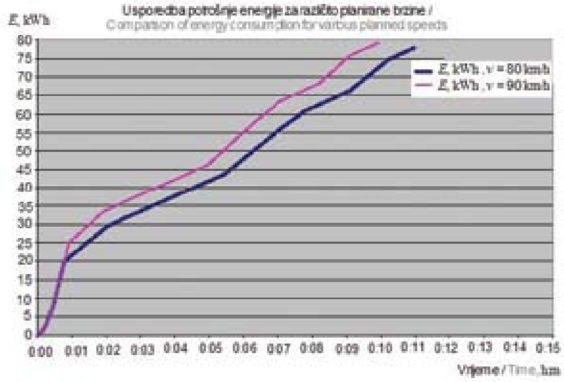
Ako planiranu brzinu iz prethodnog slučaja smanjimo sa 90 km/h na 80 km/h (vrijeme trajanja puta se povećalo za oko 10 %) ušteda energije je oko 2 %. Usporedba dobivenih rezultata je prikazana na slici 14, iz koje je vidljivo da nije došlo do značajnije uštede energije pri proporcionalnom smanjenju brzine na svim dionicama za gore navedeni profil pruge. Prema [11], ako se vrijeme trajanja puta vlaka produži za 5 %, ili smanjenjem maksimalno dozvoljene brzine vlaka ušteda energije može iznosit i do 20 %.

Proračuni simulacije kretanja vlaka pokazuju da iznos uštede energije, pri proporcionalnom smanjenju planirane brzine dionica, ne ovisi značajno o profilu pruge već o masi vlaka. Budući da ukupna masa elektromotornih vlakova nije velika, ta ušteda neće biti znatna.

4.4 Speed

If the planned speed from the previous case is reduced from 90 km/h to 80 km/h (travelling duration time increased by about 10 %), energy savings are about 2 %. The comparison of obtained results is shown in Figure 14, which reveals that significant energy savings did not occur upon proportional reduction of speed on all sections for the above stated tracks profile. According to [11], if the train travelling time is reduced by 5 %, or if the maximum train speed is reduced, energy savings can amount up to 20 %.

Train movement simulations show that the amount of energy savings, at proportional reduction of the planned section speed, do not depend significantly on the tracks profile but on the train weight. Since the total electromotor train weight is not great, these savings will not be significant.



Slika 14 — Usporedba potrošnje energije za različite planirane brzine
Figure 14 — Comparison of energy consumption for various planned speeds

5 POTROŠNJA ELEKTROVUČNE PODSTANICE

Kontaktna mreža električne željeznice napaja se preko elektrovučnih podstanica, priključenih na elektroprivrednu mrežu . Na primjeru EVP-a Zaprešić pokazat će se način proračuna potrošnje električne energije.

Za proračun utrošene energije koristi se prikazani algoritam simulacije kretanja vlaka iz kojeg se dobivaju podaci o vremenu, udaljenosti od EVP-a, kao i potrebnoj djelatnoj i jalovoj snazi za kretanje vlaka, Iz podataka o svim vlakovima koji se kreću promatranom prugom može se formirati električna mreža. Podaci o transformatorima u EVP-ima, te duljinama krakovima napajanja nužni su za proračun . Formiranje električne mreže u elektrovučnom sustavu je na određeni način specifično, jer se shema napajanja mijenja u svakom trenutku. Pojedini vlakovi ulaze i izlaze iz područja napajanja, dok se drugi vlakovi zaustavljaju, pa na taj način nestaju kao potrošačko čvorište. Nakon formiranja električne mreže slijedi elektrovučni proračun napajanja za pojedini EVP. Proračun se provodi s vremenskim korakom za željeni vremenski interval.

5.1 Elektrovučni proračun napajanja EVP Zaprešić

Prikazat će se rezultati elektrovučnog proračuna za novoizgrađeni EVP Zaprešić, koji napaja planiranu prigradsku prugu kol. Podsused Tv. – Samobor – Bregana duljine 15,5 km namijenjenu isključivo za putnički prijevoz. Pojednostavljeni uzdužni profil i vršni dvosatni maksimalni grafikon voznog reda navedene pruge s ucrtanom lokacijom EVP Zaprešić prikazani su na slici 15.

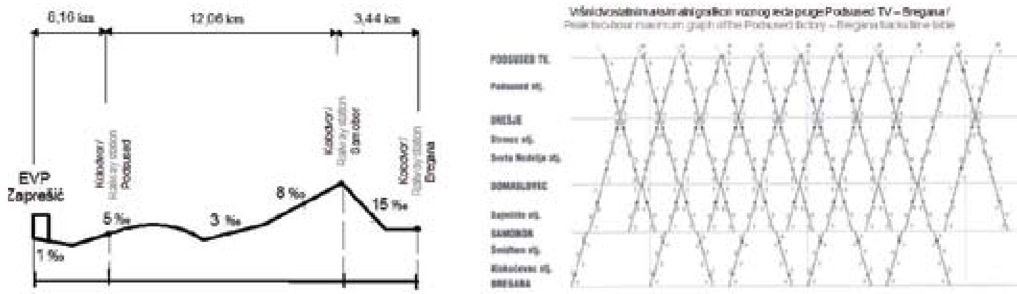
5 THE CONSUMPTION OF THE ELECTRIC TRACTION SUBSTATION

The electric railway contact network is supplied through electric traction substations connected onto the electric network. The example of the SS Zaprešić will show the manner of calculating the electric energy consumption.

For the calculation of used energy, the shown algorithm of train movement simulation is used, and data on the time, distance from the SS, as well as on the necessary active and reactive power for train movement and obtained from it. The electric network can be formed based on the data on all the trains which travel along the observed tracks. Data on the transformers in the SSs and the lengths of the supply arms are necessary for the calculation. Forming the electric network in the electric traction system is specific to a certain extent because the supply scheme changes every moment. Certain trains enter and exit the supply areas while other trains stop, and so they disappear as a consumption knot. After the formation of the electric network, electric traction supply calculation for the particular SS follows. The calculation is undertaken with a time step for the desired time interval.

5.1 Electric traction calculation of the SS Zaprešić supply

The results of the electric traction calculation will be shown for the newly built SS Zaprešić, which supplies the planned suburban 15,5 km-long tracks Podsused factory – Samobor – Bregana intended exclusively for passenger traffic. A simplified longitudinal profile and peak two-hour maximum graph of the said tracks' time-table with a mapped-in location of the SS Zaprešić are shown in Figure 15.



Slika 15 — Pojednostavljeni uzdužni profil i vršni dvosatni maksimalni grafikon voznog reda pruge Podsused Tv. – Samobor – Bregana
Slika 15 — Simplified longitudinal profile and peak two-hour maximum graph of the Podsused factory – Samobor – Bregana tracks time table.

Promatrano je vrijeme najgušćeg prometa maksimalnog prometa za vršni dvosatni maksimalni grafikon reda vožnje (od 6:00 do 8:00 h).

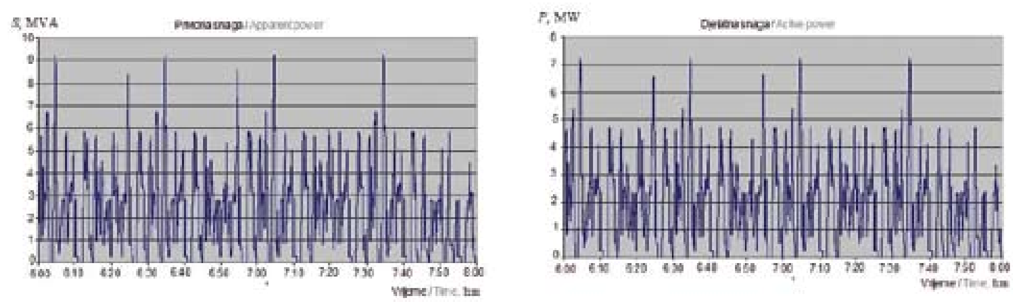
The period of the heaviest traffic of the maximum traffic for the peak two-hour maximum time-table graph (from 6:00 to 8:00) was observed.

Napajanje ove pruge se odvija voznim vodom (kontaktni vodič 100 mm² i nosivo uže 75 mm² BZ II) . Ukupna impedancija voznog voda iznosi: $0{,}181 + j \cdot 0{,}447\ \Omega$/km.

The supply of these tracks takes place through the railway electric lines (contact conductor 100 mm² and bearing rope 75 mm² BZ II). The total impedance of the railway electric lines amounts to: $0{,}181 + j \cdot 0{,}447\ \Omega$/km.

Duljina kraka napajanja EVP Zaprešić za ovu varijantu iznosi 2,38 km (8,3 km + 15,5 km). U proračunu je pretpostavljeno da EVP Zaprešić napaja 1 transformator nazivne snage S_n = 15 MVA i napona kratkog spoja u_k = 10 %. Prikaz nekih od rezultata dobivenih elektrovučnim proračunom za ovu prugu se nalazi na sljedećim slikama.

The length of the SS Zaprešić supply arm amounts to 2,38 km (8,3 km + 15,5 km) for this version. The calculation assumes that SS Zaprešić supplies 1 transformer with S_n = 15 MVA nominal power and u_k = 10 % short-circuit voltage. The presentation of some of the results obtained by electric traction calculation for these tracks can be found in the following Figures.

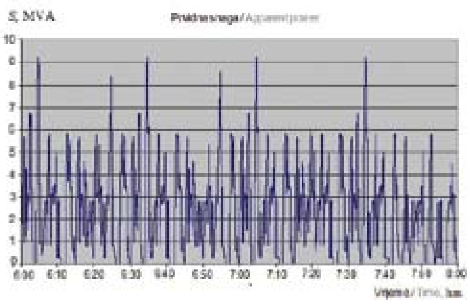


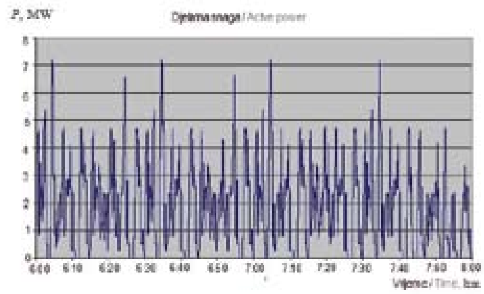
Slika 16 — Opterećenje EVP Zaprešić prividnom i djelatnom snagom pri napajanju pruge Podsused Tv. – Samobor – Bregana
Figure 16 — Loading of the ETS Zaprešić with apparent and active power upon the supply of the Podsused factory – Samobor – Bregana tracks

Sa slike 16 se može zaključiti da postoji očita razlika između prividne i djelatne električne snage, a time i potreba za kompenzacijom jalove snage pri napajanju električne vuče. Potrošnja električne energije EVP Zaprešić pri napajanju promatrane pruge za dvosatni period prikazana je na slici 17. U proračunima nije uzeta u obzir mogućnost rekupe-

Based on Figure 16 it can be concluded that there is obvious difference between the apparent and the active electric power and therefore the need for compensation of reactive power at the supply of the electric traction. Electric energy consumption of the SS Zaprešić at the supply of the observed tracks for the two-hour period is shown in Figure racije. Uz pomoć elektrovučnog proračuna moguće je razmatrati utjecaj raznih faktora na potrošnju električne energije, poput brzine vlakova i načina njihova kretanja, gustoće prometa, rekuperacije, kompenzacije jalove energije i drugo.

17. The calculations did not take into consideration the possibility of recuperation. With the help of the electric traction calculation, it is possible to analyse the impact of various factors on the electric energy consumption, such as train speed and manner of their movement, traffic density, recuperation, reactive power compensation, etc.





Slika 17 — Potrošnja električne energije EVP Zaprešić pri napajanju pruge Podsused Tv. – Samobor – Bregana
Figure 17 — Electric energy consumption of the ETS Zaprešić at the supply of the Podsused factory – Samobor – Bregana tracks

6 ZAKLJUČAK

U članku je prikazan matematički model simulacije kretanja vlaka kakav se koristi za proračune električne vuče, a uz čiju se pomoć može izračunati utrošena energija. Nakon usporedbe rezultata proračuna i mjerenja provedena je parametarska analiza utjecajnih faktora na potrošnju električne energije za elektromotorni vlak, koji prometuje na hrvatskim prigradskim željeznicama.
Rezultati dobiveni algoritmom za simulaciju kretanja vlaka i elektrovučnim proračunom uspoređeni su s izmjerenim, pa je pokazano da se izračunate struje i naponi relativno dobro podudaraju s mjerenim strujama napojnih vodova i napona na 25 kV strani EVP-a .

Na osnovi algoritma kretanja vlaka provedena je parametarska analiza utjecajnih faktora na potrošnju energije elektromotornog vlaka. Iz rezultata se može zaključiti kako nema značajnije promjene u potrošnji energije elektromotornog vlaka za radijuse krivine iznad 5 000 m, kao i to da potrošnja energije linearno raste s porastom uspona promatrane dionice pruge. Također je pokazano kako se uz mogućnost rekuperativnog kočenja, tj. povrata električne energije u mrežu može znatno smanjiti potrošnja energije elektromotornog vlaka, u nekim slučajevima i do 30 %, što naravno zavisi o profilu pruge.

Na kraju je prikazan izračun potrošnje električne energije za period dvosatnog vršnog maksimalnog prometa za EVP Zaprešić pri napajanju planirane

6 CONCLUSION

The article shows the mathematical train movement simulation model such as is used for the electric traction calculations by virtue of which the consumed energy can be calculated. After the comparison of the calculation and measurement results, the parametric analysis was undertaken of the impact factors on the electric energy consumption for the electromotor train which travels the Croatian suburban railways.

The results obtained by the algorithm for train movement simulation and by the electric traction calculation are compared with the measured results so it was revealed that the calculated currents and voltages coincide relatively well with the measured currents of the feeder currents and the voltages on the 25 kV side of the SS.

Based on the train movement algorithm, parametric analysis of the impact factors on the electromotor train electric energy consumption was undertaken. The results give rise to the conclusion that no significant change in the electromotor train energy consumption occurs for bend radiuses over 5 000 m, as well as that the energy consumption rises linearly with the increase of the climb of the observed tracks section. It has also been shown that, with the possibility of recuperative braking, that is, return of electric energy into the network, electromotor train energy consumption can be significantly reduced, in some cases even up to 30 %, which of course, depends on the tracks profile.

prigradske pruge Podsused Tv. - Samobor -Bregana. Prikazani elektrovučni proračun može poslužiti za razmatranje raznih faktora koji utječu na potrošnju električne energije s ciljem optimalne potrošnje.

Finally, the calculation of electric energy consumption was shown for the two-hour period of the maximum traffic for the SS Zaprešić at the supply of the planned Podsused factory – Samobor – Bregana suburban tracks.

The shown electric traction calculation can be used for analysing various factors which affect the electric energy consumption for the purpose of optimum consumption.

LITERATURA / REFERENCES

[1] LIU R., GOLVITCHER I. M., Energy-efficient Operation of Rail Vehicles, Transportation Research, Part A 37 (2003) 917–932, 7. July 2003

[2] MANDIĆ M., Magistarski rad – Elektroenergetski proračun napajanja kontaktne mreže 25 kV, 50 Hz, Zagreb, 2006.

[3] ŠVALJEK I., KOŽULJ T., BOŠNJAK M., Tehničko-eksploatacijski pokazatelji i značajke vučnih vozila Hrvatskih željeznica, Zagreb: HŽ -Hrvatske željeznice, 2003.

[4] MAGUEL E., TAJADDINI a., TROSINO M., KALOUSEK J., Traction, Forces, Wheel Climb and Damage in High-speed Railway Operations, ScienceDirect, Wear 265 (2008) 1446–1451, May 2008

[5] RADOJKOVIĆ B., Električna vuča, Naučna knjiga, Beograd, 1986.

[6] CHOW W. K., YU P. C. H., Simulation on Energy Use for Mechanical Ventilation an

[7] Air-conditioning (MVAC) Systems in Train Compartments, Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, PR China, March 1999

[8] DENNIS J. C., SAHA T. K., Investigation of the Propagation of Harmonic Distortion from Traction Converters into Traction and Transmission Systems, Power Engineering Society General Meeting, 2006. IEEE, 18-22 June 2006 Page(s):8

[9] HWANG H. S., Control Strategy for Optimal Compromise Between Trip Time and Energy Consumption in a High-Speed Railway, IEEE Transaction on systems, man, and cybernetics – part A: systems and humans, vol. 28, no. 6, november 1998

[10] HAIDONOG L., BAOHUA M., YONG D., WENZHENG J., SHUKUN L., Train Energy-saving Scheme with Evaluation in Urban Mass Transit Systems, Journal of Transportation systems engineering and information technology, Volume 7, Issue 5, October 2007

[11] TIROVIĆ M., Energy Thrift and Improved Performance Achieved through Novel Railway Brake Discs, ScienceDirect, Applied Energy 86 (2009) 317–324, June 2008

[12] JONG J. C., CHANG. E. F., Models for Estimating Energy Consumption on Electric Trains, Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 278 - 291, 2005

[13] UGLEŠIĆ I., Pavić I., Milardić V., Mandić M., Elektroenergetski proračun napajanja električne vuče na pruzi Podsused Tvornica – Samobor – Bregana, ožujak, 2006.

Adrese autora:

Mr. sc. **Milivoj Mandić**
milivoj.mandic@fer.hr
Prof. dr. sc. **Ivo Uglešić**
Ivo.uglesic@fer.hr
Doc. dr. sc. **Viktor Milardić**
Viktor.milardic@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva,
Unska 3
10000 Zagreb
Hrvatska

Authors' Adresses:

Milivoj Mandić, MSc
milivoj.mandic@fer.hr
Prof. **Ivo Uglešić**, PhD
Ivo.uglesic@fer.hr
Assistant prof. **Viktor Milardić**, PhD
Viktor.milardic@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing,
Unska 3
10000 Zagreb
Croatia

Uredništvo primilo rukopis:
2009-04-14

Prihvaćeno:
2009-06-30

Manuscript received on:
2009-04-14

Accepted on:
2009-06-30

ANALIZA PODEŠENJA DISTANTNE ZAŠTITE PROVEDBOM PRIMARNIH POKUSA

ANALYSIS OF DISTANCE PROTECTION SETTING BY PERFORMING PRIMARY TRIALS

Kristijan Frlan, Opatija, Hrvatska – Ante Marušić – Juraj Havelka, Zagreb, Hrvatska

Na području zapadnog dijela elektroenergetskog sustava (EES-a) Hrvatske rekonstruirani su vodovi 110 kV prijenosne mreže radi poboljšanja sigurnosti i kvalitete pogona. Specifičnost razmatranog dijela EES-a je da u okruženju postoji samo jedan snažni izvor napajanja. To su dvije termoelektrane, Plomin 1 na naponskoj razini 110 kV i Plomin 2 na naponskoj razini 220 kV, smještene na istoj lokaciji. Kvar nastao u razmatranoj mreži napaja se gotovo isključivo iz jedne pojne točke. Navedeni nerazmjer u distribuciji struja kvara nerijetko rezultira pojavom takvih uvjeta koji ne jamče ispravno djelovanje zaštitnih releja na vodovima.
Relejna zaštita vodova postala je složeni sustav. Korištenjem telekomunikacijskih resursa zajedno s numeričkim zaštitnim relejima pojavila se potreba za ispitivanjem cjelokupnog sustava kao cjeline, a ne samo pojedinačnih dijelova. Provedbom primarnih pokusa u prijenosnoj mreži 110 kV ispitano je djelovanje sustava zaštite u okruženju kvara.
U radu su opisani pripremni radovi i sama provedba primarnih pokusa na T-spoju 110 kV-og voda TE Plomin – TS Šijana – TS Vinčent.

In the territory of the western part of the Croatian electrical power system (EPS) lines 110 kV of the transmission network have been reconstructed for the purpose of improvement of safety and drive quality. The particularity of the observed part of the EPS is that its environment includes only one powerful power supply source. Those are two thermal power plants on the same location, Plomin 1 with the voltage level of 110 kVand Plomin 2 with the voltage level of 220 kV. The fault which occurred in the observed network is charged almost entirely from one supply point. The said inconsistence in the fault currents distribution often results in the occurrence of such conditions that do not guarantee proper operation of the transmission lines' protection relays.
Relay protection of the transmission lines has become a complex system. The use of telecommunication resources together with numerical protection relays has given rise to the need for verification of the entire system as a whole and not only its individual parts. The performance of primary trials in the transmission network 110 kV was used to test the operation of the protection system in the fault ambience.
The work describes the preparatory work and the very performance of primary trials at the T-junction of the 110 kV transmission line of Plomin thermal power plant – Šijana substation – Vinčent substation.

Ključne riječi: distantna zaštita; ispitivanje s kraja na kraj; primarni pokusi; program CAPE; T-spoj
Key words: distance protection; end-to-end trial; primary trials; CAPE programme; T-junction

1 UVOD

Cilj testiranja provedbom primarnih pokusa u hrvatskom elektroenergetskom sustavu bio je provjera rada distantne telezaštitne sheme. Na istarskom poluotoku postoje dvije termoelektrane, jedna ima snagu od 156 MVA i naponsku razinu od 110 kV, a druga ima snagu od 263 MVA i naponsku razinu od 220 kV. Obje su smještene na istoj lokaciji. Svaki kvar koji nastaje, neovisno o lokaciji, napajan je, bilo direktno ili indirektno, iz navedenih elektrana koje su jedini jaki izvor u regiji. Nejednolikost u tokovima snaga i doprinosu struji kratkog spoja može dovesti do krive prorade distantne zaštite. Kako bi se poboljšala sigurnost energetskog sustava izgrađen je 110 kV dalekovod baziran na principu T-spoja (krajnje točke T-spoja su: TE Plomin – TS Šijana – TS Vinčent) i štićen je distantnom telezaštitom. Podešenje zona štićenja je napravljeno pomoću CAPE programske podrške u kojoj su napravljene simulacije raznih kvarova pri različitim konfiguracijama mreže.

T-spoj nije uobičajen u hrvatskom elektroenergetskom sustavu pa je stoga to prva vrsta
T-voda koji je analiziran u zapadnom dijelu hrvatskog elektroenergetskog sustava. Upravo je to i razlog zbog kojeg su se provela primarna ispitivanja.

Zbog toga što ovakva ispitivanja zahtijevaju znatnu pripremu, cijeli posao je bio podijeljen u tri faze:

— simulacija pomoću CAPE programske podrške kako bi se dobili općeniti podaci o radu sustava i vrijednosti napona i struja tijekom ispitivanja s kraja na kraj,
— GPS sinkronizirano ispitivanje s kraja na kraj kako bi se provjerila podešenja zaštite i telekomunikacijskog sustava,
— primarno ispitivanje.

2 HRVATSKI ELEKTROENERGETSKI SUSTAV

Hrvatski prijenosni elektroenergetski sustav podijeljen je u četiri područja (slika 1). Zapadni dio sustava koji se razmatra u radu sastoji se od vodova 220 kV i 110 kV. Dvije termoelektrane smještene na istočnom dijelu poluotoka Istre jedina su dva snažna čvorišta u tom dijelu EES-a.

1 INTRODUCTION

The objective of testing by virtue of primary trials in the Croatian electrical power system was to verify the operation of the distance teleprotection scheme. There are two thermal power plants on the Istrian Peninsula, one operates with the power of 156 MVA and voltage level of 110 kV, and the other at 263 MVA of power and at the voltage level of 220 kV. Both are at the same location. Each occurring fault, independent of its location, is supplied, either directly or indirectly, from the said power plants which are the only powerful source in the region. The disparity of power flows and contributions to the short circuit current can bring about an improper trip of the distance protection. In order to improve the safety of the energy system, a transmission line has been constructed which is based on the principle of the T-junction (end points of the T-junction are: Plomin TPP – Šijana substation – Vinčent substation) and it is protected by distance teleprotection. The setting of protection zones was made by virtue of the CAPE programme support in which simulations of various faults were undertaken at different network configurations.

The T-junction is not usual for the Croatian electrical power system so this is the first type of the T-junction transmission lines which has been analysed in the western part of the Croatian energy power system. This is exactly the reason for the undertaking of primary trials.

As these kinds of trials require significant preparation, the entire work was divided in three phases:

— simulation by virtue of the CAPE programme support in order to obtain general data on the operation of the system and the value of voltages and currents during the end-to-end study,
— GPS end-to-end synchronous study in orde r to verify the protection and telecommunication system settings,
— primary study.

2 CROATIAN ELECTRICAL POWER SYSTEM

The Croatian transmission electrical power system is divided into four zones (Figure 1). The western part of the system analysed in the work consists of the transmission lines 220 kV and 110 kV. Two thermal power plants located in the eastern part of the Istrian peninsula are the only two powerful hubs in that part of the electrical power system.

Slika 1 — Hrvatski elektroenergetski sustav
Figure 1 — The electrical power system of the Republic of Croatia

Termoelektrana Plomin 1 (156 MVA) spojena je na naponsku razinu 110 kV, a Plomin 2 (263 MVA) na naponsku razinu 220 kV. Veza između 220 kV i 110 kV naponske razine realizirana je preko tri autotransformatora (150 MVA). Termoelektrane su spojene vodovima 220 kV s trafostanicama TS Melina 400/220/110 kV i TS Pehlin 220/110 kV i vodom 110 kV s trafostanicom TS Lovran. Na sjeveru Istre EES Hrvatske povezan je sa susjednim sustavom Slovenije vodom 110 kVTS Buje – TS Kopar (slika 2).

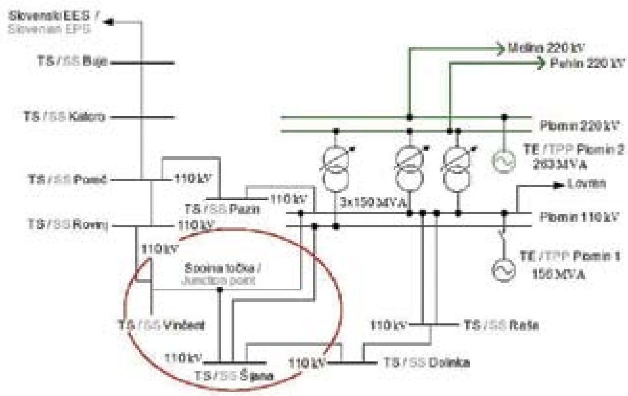
Hrvatski elektroenergetski sustav je spojen sa susjednim zemljama i zajedno s njima u Europsku UCTE sinkroniziranu mrežu. Hrvatski EES je po veličini jedan od najmanjih u Europi, ali je zbog zemljopisnog položaja bitan pri povezivanju istočnog i zapadnog UCTE sustava.

Glavna zaštita na svim vodovima je distantna. Releji su elektromehaničke, statičke i numeričke izvedbe. Prilikom pojave kvara isti se napaja gotovo isključivo iz čvorišta Plomin 220/110 kV kao jedinog snažnog izvora. Takva raspodjela toka struje kvara posljedica je konfiguracije EES-a na razmatranom području.

The Plomin 1 thermal power plant (156 MVA) is connected to the voltage level of 110 kV and the Plomin 2 (263 MVA) to the voltage level of 220 kV. The connection between the voltage levels of 220 kV and 110 kV was realized through three autotransformers (150 MVA). The thermal power plants are connected by transmission lines of with the Melina substation 400/220/110 kV and the Pehlin substation 220/110 kV and by the transmission line of 110 kV with the Lovran substation 110 kV. In the north of Istria, the Croatian EPS is connected to the neighbouring system of Slovenia by transmission lines of 110 kV SS Buje – SS Kopar (Figure 2).

The Croatian electrical power system is connected with the neighbouring countries and together with them to the European UCTE synchronised network. The Croatian EPS is one of the smallest in Europe according to its size, but because of its geographical position, it is crucial in connecting the eastern and the western UCTE systems.

The main protection in all the transmission lines is distance. Relays are of electromechanical, static and numerical design. When it occurs, a fault is charged almost exclusively from the Plomin hub 220/110 kV as the only powerful source. Such distribution of the fault current flow is a consequence of the EPS configuration in the observed area.



Slika 2 — Zapadni dio Hrvatskog EES-a
Figure 2 — Western part of the Croatian EPS

2.1 T-spoj TE Plomin –TS Šijana –TS Vinčent

Vod realiziran na principu T-spoja između TE Plomin, TS Šijana i TS Vinčent konstruiran je za naponsku razinu 220 kV, ali je privremeno u pogonu pod naponom 110 kV. Dužine i impedancije pojedinih vodova prikazane su u tablici 1. Utjecaj različite dužine pojedinog odvojka i nejednak doprinos struji kvara uvjetovali su specifičan pristup prilikom određivanja podešenja za pojedine releje.

2.1 T-junction of TPP Plomin – Šijana substation –Vinčent substation

The transmission line realized on the principle of a T-junction between the TPP Plomin, Šijana substation and Vinčent substation was constructed for the voltage level of 220 kV, but it is currently operating at the voltage of 110 kV. Lengths and impedances of certain transmission lines are shown in Table 1. The impact of different lengths of certain extensions and unequal contribution to the fault current gave rise to a specific approach during the determination of the setting for certain relays.

Tablica 1 – Podaci za T-spoj
Table 1 – Data for the T-junction

Grana / Branch	Dužina / Length, km	Z_d, Ω	Z_0, Ω
Plomin – Spojna točka / Junction point	33,1	1,832+ j 13,83	6,62 + j 39,85
Vinčent – Spojna točka / Junction point	24,34	2,92 + j 10,17	12,04 + j 26,1
Šijana – Spojna točka / Junction point	10,11	1,214 + j 4,22	3,514 + j 10,8

3 KONFIGURACIJA RELEJNE ZAŠTITE

3.1 Podešenje distantne zaštite

Praksa je pokazala da je za zaštitu vodova najbolja opcija uporaba uzdužne diferencijalne zaštite. U ovom slučaju to nije bilo moguće realizirati, jer su u postojećim objektima numerički releji već bili ugrađeni u svojim zasebnim sustavima upravljanja i zaštite. Zbog toga je odabrana distantna zaštita s komunikacijskim vezama između releja. Pri tom

3 RELAY PROTECTION CONFIGURATION

3.1 Distance protection setting

Practice has shown that the best option for the protection of the transmission lines is the use of longitudinal differential protection. In this case, this cannot be realized because numerical relays, in their separate management and protection systems, were already installed in the existing facilities. Therefore, distance protection with telecommunitreba napomenuti da su korišteni releji različitih proizvođača i različitih generacija.

Algoritam distantne zaštite djeluje na način da određuje udaljenost do mjesta kvara mjerenjem impedancije, odnosno struje i napona. Nejednak doprinos struji kvara s pojedinih krajeva T-spoja uvjetovao je podešenja pojedinih releja. Impedancija koju mjeri relej ovisi o struji koja se mjeri na mjestu ugradnje strujnog mjernog transformatora, što u nekim slučajevima može rezultirati pogrešnim proradama releja [1].

Koncepcija distantne zaštite s komunikacijom među relejima zahtijeva pouzdane komunikacijske veze za prijenos signala za djelovanje distantne zaštite. Relej koji detektira kvar u prvoj zoni $1(Z_1)$ šalje signal za ubrzanje djelovanja na drugi kraj voda. Ukoliko je relej koji je primio signal detektirao kvar u zoni pobude, izdaje nalog za ubrzani isklop bez obzira na podešenu vremensku odgodu u višim zonama. Obično se zona $1(Z_1)$ podešava na 85 % do 90 % impedancije štićenog voda. Rezerva od 10 % do 15 % ostvaruje se zbog moguće netočnosti mjernih transformatora i samog algoritma releja, čije bi greške mogle dovesti do pogrešne prorade releja. Zona pobude koja omogućuje ubrzano djelovanje nakon primitka signala za djelovanje obično se podešava na 120 % do 130 % impedancije štićenog voda (Zona $2(Z_2)$) [2].

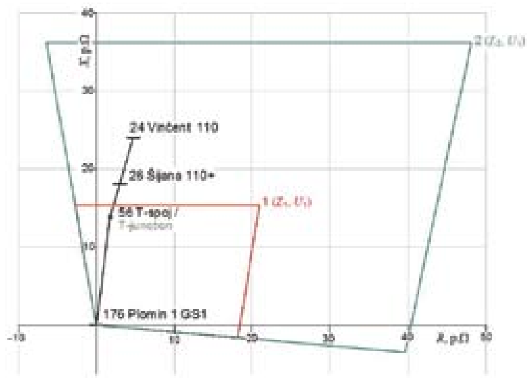
Programom CAPE modelirana je mreža prijenosnog područja (PrP) Rijeka, te su provedene simulacije različitih vrsta kvarova na različitim lokacijama na promatranom T-vodu. Analizom dobivenih rezultata došlo se do zaključka da relej u TE Plomin ne griješi u određivanju mjesta kvara bez obzira na tip i mjesto kvara, dok relej u TS Šijana, a posebice u TS Vinčent griješi. Pogreške u određivanju lokacije kvara posljedica su utjecaja dodatnih spojnih mjesta u zoni štićenja ili utjecaja otpora na mjestu kvara. Zbog navedenih razloga podešenja releja provedena su na način da zona $1(Z_1)$ svakog releja doseže preko spojne točke, dok je zona pobude koja omogućava ubrzano djelovanje povećana do zone $4(Z_4)$. Na slikama 3, 4 i 5 prikazana su podešenja pojedinih releja.

cation connections between relays was chosen. It should be added that the used relays are of different producers and different generations.

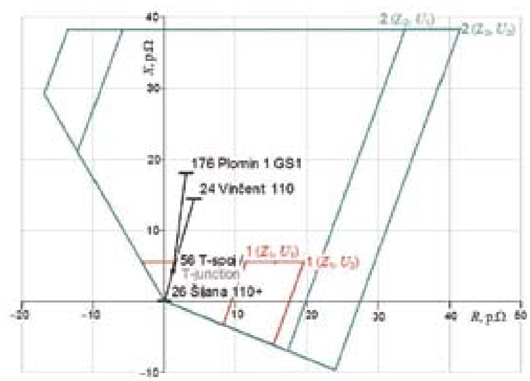
The distance protection algorithm works so that it determines the distance to the location of the fault by measuring impedance, that is, the current and the voltage. The settings of certain relays were dependant on unequal contribution to the fault current from certain ends of the T-junction. The impedance measured by the relay depends on the current measured at the point of installation of the current measuring transformer, which, in some cases, can result in improper relay trips [1].

The distance protection concept with inter-relay communication requires reliable communication links for signal transmission for the effect of the distance protection. The relay which detects the fault in the first (Z_1) zone sends the signal for acceleration of the effect to the other end of the power line. If the relay which has received the signal detects the fault in the actuation zone, it issues an order for accelerated switch-off regardless of the set time delay in higher zones. The (Z_1) zone is usually set at 85 % to 90 % of the protected transmission line impedance. A backup of 10 % up to 15 % is realized because of the possible incorrectness of the measuring transformers and the very relay algorithm which errors could lead to an improper tripping of the relay. The actuation zone which enables accelerated operation after the receipt of the signal for effect is usually set at 120 % up to 130 % of the protected transmission line impedance ($2(Z_2)$ Zone) [2].

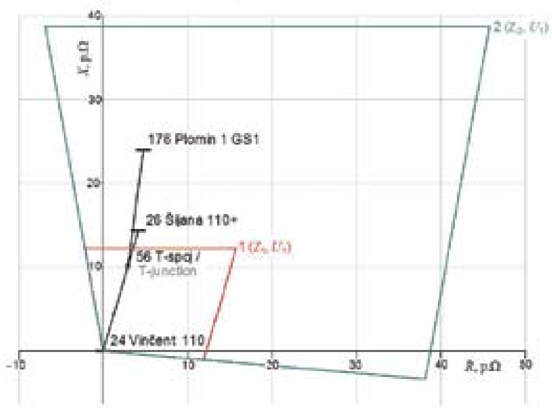
The CAPE programme was used to model the Rijeka transmission area network and the simulations of different types of faults have been implemented at different locations in the observed T-junction power line. The analysis of the obtained results gave rise to the conclusion that the relay in the Plomin thermal power plant does not mistake in determining the fault location regardless of the type and location of the fault, while the relay in the Šijana substation, just like the one in the Vinčent substation, does. The errors in determining the location of the fault are a consequence of the impact of additional junction points in the zone of protection or resistance impact at the location of the fault. Due to the stated reasons, the relay settings were done so that zone $1(Z_1)$ of each relay reaches beyond the junction point while the actuation zone, which enables accelerated effect, is extended to zone $4(Z_4)$. Figures 3, 4 and 5 show the settings of certain relays.



Slika 3 — Podešenje releja za TE Plomin
Figure 3 — Setting of the relay for the Plomin thermal power plant



Slika 4 — Podešenje releja za TS Šijana
Figure 4 — Setting of the relay for the Šijana substation



Slika 5 — Podešenje releja za TS Vinčent
Figure 5 — Setting of the relay for the Vinčent substation

Isklopna logika podešena je na sljedeći način:

— jednopolni isklop za jednopolne kvarove, i tropolni isklop za višefazne kvarove,
— automatski ponovni uklop za jednopolne kvarove uz beznaponsku pauzu od 1,2 s i au-

The switch-off logics are set as follows:

— one-pole switch-off for one-pole faults and three-pole switch-off for multi-phase faults,
— automatic re-switch-on for one-pole faults with voltage-free pause of 1,2 s and automatic

tomatski ponovni uklop za višepolne kvarove uz beznaponsku pauzu od 0,3 s,

- automatski ponovni uklop dozvoljen je ukoliko je kvar detektiran u zoni 1, ili nakon prijama signala za ubrzanje djelovanja uz detekciju kvara u zoni pobude.

3.2 Konfiguracija telekomunikacijskog sustava

Komunikacijski sustav između releja ostvaren je telekomunikacijskim uređajima koji prenose signale za djelovanje između pojedinih releja. Relej koji djeluje u zoni 1 izdaje nalog za isklop vlastitog prekidača i istodobno šalje signal prema ostala dva releja, slika 6. Prvi komunikacijski uređaj (telekom uređaj 1) prima signal iz pripadajućeg mu releja kao naponski impuls, pretvara ga u analogni frekvencijski signal (887 Hz) i šalje ga prema drugom komunikacijskom uređaju (telekom uređaj 2). Drugi uređaj pretvara analogni frekvencijski signal u digitalni signal koji se putem digitalne mreže šalje prema ostalim relejima, odnosno ostalim komunikacijskim uređajima (telekom uređaj 2).

Radi povećanja pouzdanosti komunikacijske mreže realiziran je drugi neovisni (rezervni) komunikacijski put. Relej koji prorađuje u zoni 1 šalje signal direktnim putem prema ostala dva releja. Rezervni put je ostvaren na način da komunikacijski uređaj dobiveni signal prosljeđuje prema onom kraju koji nije izvor signala za proradu.

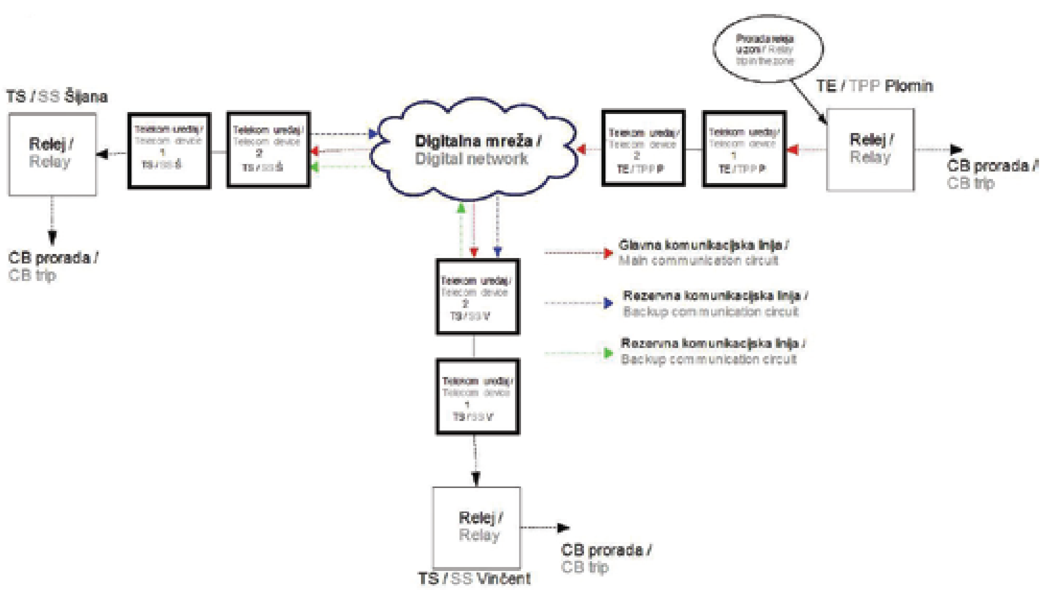
re-switch-on for multi-phase faults with a voltage-free pause of 0,3 s,

- automatic re-switch-on is allowed only if the fault is detected in zone 1, or after the receipt of the signal for accelerated effect with the detection of the fault in the actuation zone.

3.2 Telecommunication system configuration

The communication system between the relays is realized by telecommunication devices which transmit signals for effect between particular relays. The relay which operates in zone 1 issues the order for switch-off of its own breaker and simultaneously sends a signal towards the other two relays, Figure 6. The first communication device (telecom device 1) receives a signal from the pertaining relay as a voltage impulse, transforms it into an analogous frequency signal (887 Hz) and sends it towards the other communication device (telecom device 2). The other device transforms the analogous frequency signal into a digital signal which is sent through a digital network towards the other relays, that is, towards the other communication devices (telecom device 2).

For the purpose of increased reliability of the communication network, another independent (backup) communication path is realized. The relay which trips in zone 1 sends a signal directly towards the other two relays. The backup path is realized in such a manner that the communication device forwards the received signal to that end which is not the source of the trip signal.



Slika 6 — Telekomunikacijski sustav

Figure 6 — The telecommunication system

Veza između komunikacijskih uređaja neprestano se nadzire. Uređaji međusobno razmjenjuju analogne signale (2 720 Hz) koji se pretvaraju u digitalni oblik i šalju prema drugim uređajima. Ti signali služe za provjeru komunikacije među pojedinim uređajima. Ukoliko pojedini uređaj ne primi komunikacijski signal znači da je došlo do prekida veze između pojedinih uređaja i tada je cijeli sustav relejne zaštite neraspoloživ. Na slici 6 prikazan je blok dijagram komunikacijskih veza među relejima.

4 SIMULACIJA POMOĆU CAPE PROGRAMA

Da bi se dobile smjernice o ponašanju sustava prilikom kvarova u mreži, provedene su brojne simulacije programom CAPE. CAPE (engl. Computer-Aided Protection Engineering) komercijalni je program namijenjen inženjerima koji se bave relejnom zaštitom. Podaci koji se mogu dobiti kao rezultat simulacije struje su kvara i naponske prilike, te je program pogodan za definiranja podešenja za distantne releje. Program sadrži module koji omogućavaju analizu kvarova u mreži, analize koje pomažu pri budućem planiranju razvoja mreža i analize djelovanja releja.

Da bi se dobio uvid u ispravnost djelovanja sustava relejne zaštite i komunikacijskog sustava provedeni su primarni pokusi. Primarni pokusi izvedeni su na stupu broj 49 od TE Plomin prema točki čvorišta. Lokacija stupa je na 49,46 % dužine odvojka TE Plomin – Spojna točka (gledano iz smjera TE Plomin), odnosno 16,234 km od TE Plomin. Koristeći modul za kratki spoj [3] i grafički i koordinacijski modul [4] odabran je stup 49 i to iz razloga što se prema podacima dobivenim iz simulacija nalazi u zoni 1 releja u TE Plomin i u zoni 2 relejima u TS Šijana i TS Vinčent. Simulacije su također pokazale da releji u TS Šijana i TS Vinčent najviše griješe prilikom određivanja lokacije kvara.

Jednopolni i dvopolni kvarovi simulirani su radi kontrole isklopne logike.

Rezultati CAPE simulacije su prikazani u tablicama 2 i 3.

5 ISPITIVANJE S KRAJA NA KRAJ

Prije provedbe primarnih pokusa provedeno je ispitivanje s kraja na kraj sekundarnim injektiranjem analognih veličina u relej. Ovakav način ispitivanja koristi se prilikom puštanja u pogon

The link between communication devices is constantly supervised. The devices exchange analogous signals (2 720 Hz) which transform into digital form and are sent towards the other devices. Those signals serve for the verification of the communication between certain devices. In case a particular device does not receive a communication signal that means that a connection interruption has occurred between certain devices and then the entire relay protection system is unavailable. Figure 8 shows the block diagram of communication connections between the relays.

4 SIMULATION BY VIRTUE OF THE CAPE PROGRAMME

In order to obtain guidelines on the behaviour of the system when faults occur in the network, numerous simulations by virtue of the CAPE programme were performed. CAPE (Computer-Aided Protection Engineering) is a commercial programme intended for engineers who are involved in relay protection. Data which can be obtained as a result of the simulation are fault currents and voltage circumstances and the programme is fit for defining distance relays settings. The programme contains modules which enable the analysis of the network faults, analyses which facilitate the future planning of network development and analyses of relay effects.

In order to gain insight into proper relay protection system and communication system operation, primary trials have been preformed. Primary trials were performed on tower number 49 of the Plomin thermal power plant towards the hub point. The tower location is at 49,46 % of the length of the extension of Plomin TPP - junction point (viewed from the direction of Plomin TPP), that is, 16,234 km from the Plomin TPP. Using the short circuit modulus and the graphic and coordination modulus, tower 49 was chosen, namely, because, according to data obtained from the simulations, it is located in zone 1 of the Plomin TPP relay and in zone 2 of the Šijana substation and Vinčent substation relays. Simulations also showed that the relays in the Šijana and Vinčent substation are the most erroneous during the determination of the fault location.

One-pole and two-pole faults were simulated for the purpose of control of the switch-off logics.

The results of the CAPE simulation are shown in Tables 2 and 3.

5 END-TO-END STUDY

Before the implementation of primary tests, an end-to-end study was performed by secondary injection of

Tablica 2 – Doprinosi pojedinih struja za kvar na stupu 49 (za razne kvarove)
Table 2 – Contributions of certain currents to the fault on tower 49 (for different faults)

Lokacija / Location	Vrsta kvara / Type of fault	, A (Simulirane struje u releju / Simulated currents in the relay)			
		I_{L1}	I_{L2}	I_{L3}	$3I_0$
Plomin	L1-E	3 906∠82,441°	120∠90,549°	120∠90,419°	3 667,8∠-81,978°
	L1-L2	0,6∠61,791°	3 963∠-173,395°	3 963,0∠6,609°	/
Šijana	L1-E	1 311∠77,872°	130,2∠86,683°	130,2∠-86,875°	1 568,4∠-79,342°
	L1-L2	0,6∠89,807°	1 164,6∠-167,628°	1 164,6∠12,351°	/
Vinčent	L1-E	572,4∠77,529°	11,4∠123,354°	11,4∠123,1431°	551,4∠-78,370°
	L1-L2	0,000∠-136,181°	374,2∠-167,876°	574,2∠12,136°	/

Tablica 3 – Naponi na sabirnicama za kvar na stupu 49 (za razne kvarove)
Table 3 – Voltages on the busbars for the fault on tower 49 (for different faults)

Lokacija / Location	Vrsta kvara / Type of fault	V, kV(Fazni naponi na lokaciji releja / Phase voltages at the location of the relay)		
		V_{L1}	V_{L2}	V_{L3}
Plomin	L1-E	32,167 9∠0,0°	62,098 5∠-115,7°	61,846 8∠115,7°
	L1-L2	65,507 8∠-0,1°	44 630 0∠-138,6°	43,660 9∠137,2°
Šijana	L1-E	32,167 9∠0,0°	62,098 5∠-115,7°	61,846 8∠115,7°
	L1-L2	65,211 0∠-0,1°	36,737 8∠-150,2°	38,022 6∠151,2°
Vinčent	L1-E	31,817 5∠-0,1°	62,381 4∠-116,8°	62,555 0∠116,6°
	L1-L2	65,138 4∠-0,1°	37,236 7∠-149,2°	38,310∠150,0°

novih sustava relejne zaštite i pogodan je za testiranje cjelokupnog sustava zaštite, kao što su testiranja djelovanja zaštite na prekidače, testiranje komunikacijskog sustava te testiranje ispravnosti podešenja samih releja.

Za provedbu ispitivanja s kraja na kraj potrebno je provesti sljedeće pripreme:

— provjeriti podešenja u pojedinim relejima,
— postaviti ispitivački tim na svakom kraju voda (2 inženjera na svakoj strani),
— sinkronizirati ispitne uređaje,
— pokrenuti programsku podršku i module za ispitivanje s kraja na kraj,
— definirati ispitivanje (mjesto i vrste kvara),
— definirati korake za sve strane (prije, poslije i za vrijeme kvara).

5.1 Program i modul za ispitivanje s kraja na kraj

Za provedbu testova korišten je Omicron sustav za sekundarna ispitivanja. Tri ispitna uređaja, svaki na jednom kraju 110 kV-nog T-spoja, sinkronizirani su putem GPS modula.

analogous dimensions into the relay. This manner of testing is used upon putting into operation new relay protection systems and it is suitable for testing the entire protection system, such as testing the effect of the protection on the breakers, testing the communication system and testing the proper setting of the very relays.

For the purpose of implementation of end-to-end studies, the following preparations need to be undertaken:

— check the settings in certain relays,
— set up a trial team at each end of the power line (2 engineers on each side),
— synchronize testing devices,
— start up the programme support and modulus for end-to-end studies,
— define the study (location and types of fault),
— define the steps for all aspects (before, after and during the fault).

5.1 End-to-end study programme and modulus

For the implementation of the tests, the Omicron system for secondary trials was used. Three test devices, each at one end of the 110 kV T-junction were synchronized by virtue of the GPS modulus.

5.2 Definiranje ispitivanja (lokacija i kvarovi)

Program CAPE korišten je za simulaciju kvarova na lokaciji stupa 49 od TE Plomin prema spojnoj točki na 49,46 % dužine voda (16,234 kV) kao što je opisano u poglavlju 4. Simulirani kvarovi su bili jednopolni (L1-E) i dvopolni (L1-L2). Na taj način je zaštita testirana za jednopolne kratke spjeve između faze i zemlje i za dvopolne kratke spojeve.

5.3 Definicija sekvenci

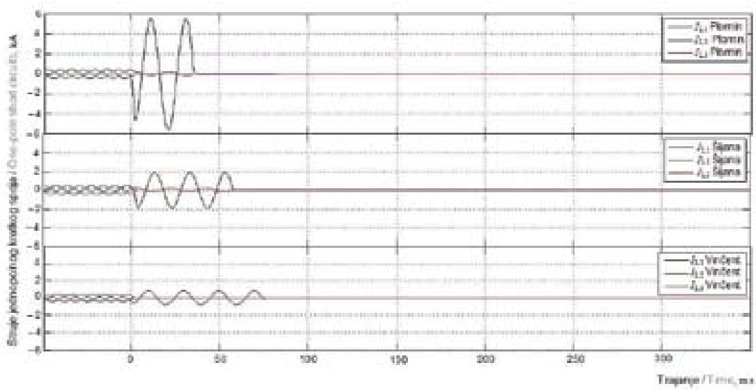
Ispitivanje s kraja na kraj je provedeno pomoću programskog modula (engl. state sequencer). Strujne i naponske vrijednosti dobivene su simulacijom u CAPE programskoj podršci i korištene su za ispitivanje pojedinih releja, ovisno o lokaciji na kojoj su postavljeni. Svaka ispitna sekvenca sastojala se od vrijednosti prije, za vrijeme i poslije kvara. Podešenja za uvjete prije kvara su bila ista za sve releje. Struja prije kvara na lokaciji stupa 49 iznosila je 300 A, što je uobičajeno opterećenje dalekovoda. Stanje za vrijeme kvara dobiveno je iz CAPE programske podrške. Slika 7 pokazuje valne oblike definiranih sekvenci, na mjestu mjerenja, za vrijeme jednopolnog kratkog spoja.

5.2 Definition of the study (location and faults)

The CAPE programme was used for simulation of faults at the location of tower 49 from the Plomin TPP towards the junction point at 49,46 % of length of the transmission line (16,234 kV) as described in Chapter 4. Simulated faults were one-pole (L1-E) and two-pole (L1-L2). In such a way the protection was tested for one-pole short circuits between phase and ground and for two-pole short-circuits.

5.3 Definition of sequences

End-to-end study was performed by virtue of the state sequencer programme modulus. Current and voltage values were obtained by virtue of simulation in the CAPE programme support and used for the study of certain relays, depending on their location. Each trial sequence consisted of the value before, during and after the fault. Settings for the pre-fault conditions were equal for both relays. The pre-fault current at the location of tower 49 amounted to 300 A which is usual for the power-transmission line loading. The state during the fault was obtained from the CAPE programme support. Figure 7 shows the wave forms of the defined sequences at the location of the measurement and at the moment of the one-pole short-circuit.



Slika 7 — Vrijednosti struja za ispitivanje s kraja na kraj po sekvencama za jednopolni kratki spoj (L1-E) na stupu 49

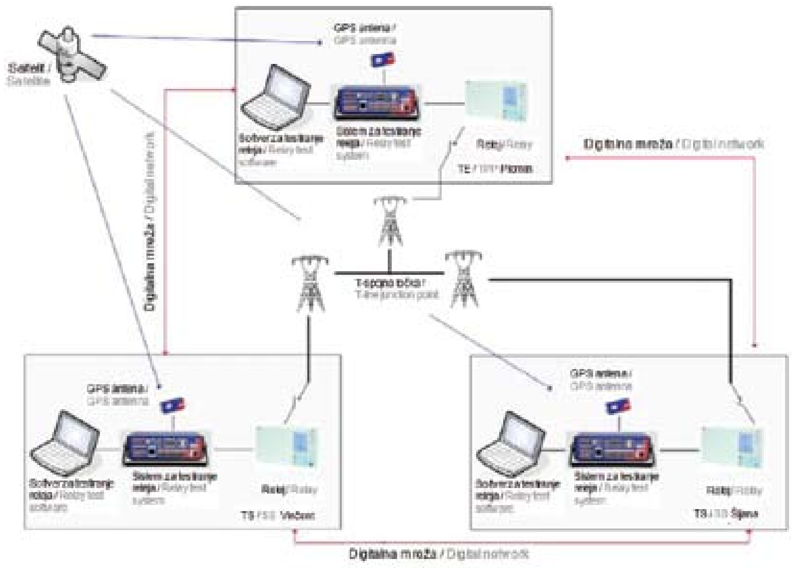
Figure 7 — Values of the currents for the end-to-end trial according to the sequences for a one-pole short circuit (L1-E) on tower 49

5.4 Priprema i početak ispitivanja

Tri ispitna uređaja za sekundarna ispitivanja vremenski su međusobno sinkronizirana putem GPS sustava (slika 8). Pripremljeni testovi injektiraju se u releje kada GPS modul ispitnog uređaja primi satelitski signal. Na taj način sva tri uređaja započinju testiranje u isto vrijeme.

5.4 Preparation and beginning of the study

Three testing devices for secondary trials were temporally inter-synchronized by virtue of the GPS system (Figure 8). The prepared tests were injected into the relays when the testing device GPS modulus received the satellite signal. In such a way, all three devices initiated the test at the same time.



Slika 8 — Konfiguracija sustava za ispitivanje s kraja na kraj
Figure 8 — Configuration of the end-to-end trial system

Procedura ispitivanja bila je definirana na sljedeći način:

— instrumenti za testiranje se podešavaju s GPS sinkroniziranim vremenom,
— na računalu se pokreće simulacijski program i spaja se na opremu,
— inženjeri na oba kraja voda komuniciraju i odabiru odgovarajuće ispitivanje, unose parametre potrebne za ispitivanje i započinju s ispitivanjem:

· fazorske vrijednosti napona i struja te vrijeme ispitivanja prenose se RS232 protokolom iz programske podrške na računalu u ispitnu opremu,
· vrijeme iz GPS prijamnika i vrijeme ispitivanja iz programa stalno se uspoređuju,
· kada je vrijeme u prijamniku identično vremenu ispitivanja, tada se istodobno pokreće testiranje na svakom kraju voda.

Releji su bili testirani simulacijskim signalom prilikom čega vod nije bio u pogonu. Provedeni su testovi za jednopolni (L1-E) i dvopolni (L1-L2) kvar bez djelovanja na prekidač i za jednopolni kvar (L1-E) s djelovanjem na prekidač.

5.5 Rezultati ispitivanja

Analiza djelovanja releja provedena je na temelju zapisa numeričkih releja. Rezolucija snimanja je 0,5 ms za relej u TE Plomin i TS Vinčent, te 1 ms za relej u TS Šijana. Relej u TE Plomin detektirao je kvar u zoni 1(Z_1), a releji u TS Vinčent i TS Šija-

The trial procedure is defined as follows:

— testing instruments are set with GPS-synchronized time,
— the simulation programme is launched on the computer and connected to the equipment,
— engineers at both ends of the transmission lines communicate and choose the adequate trial, introduce parameters necessary for the trial and begin with the trial:

· phasor voltage and current values and the trial time are transmitted by the RS232 protocol from the programme support in the computer into the testing equipment,
· the time from the GPS receiver and the trial time from the programme are constantly compared,
· when the time in the receiver is equal to the trial time, then the testing is simultaneously launched at each end of the power line.

The relays were tested by simulation signal whereat the transmission line was out of operation. Tests were performed for the one-pole (L1-E) and two-pole (L1-L2) fault without effect on the breaker and for the one-pole fault with effect on the breaker.

5.5 Results of the trial

The analysis of the relay effect was undertaken based on the numerical relays records. The recording resolution is 0,5 ms for the relay at the Plomin TPP and Vinčent substation, and 1 ms for the Šijana substation relay. The relay at the Plomin TPP na u zoni $2(Z_2)$. Relej u TE Plomin djelovao je bez vremenskog zatezanja, a preostala dva releja djelovala su nakon primitka signala za ubrzanje djelovanja (bez ubrzanog djelovanja imali bi vremensko zatezanje od 500 ms). Nakon analize zapisa numeričkih releja može se zaključiti sljedeće:

— relej u TE Plomin izdaje nalog za isklop 24 ms nakon nastanka kvara,
— na osnovi injektiranih sekundarnih veličina relej je izračunao da je kvar nastao 15,7 km odnosno na 47,5 % dužine štićenog voda za kvar L1-E, a za kvar L1-L2 na 16,4 km odnosno 49,6 %,
— relej u TE Plomin izdaje nalog za slanje signala za ubrzanje djelovanja 24 ms nakon nastanka kvara,
— relej u TS Šijana prima signal 48 ms nakon nastanka kvara i izdaje nalog za isklop prekidača. Vrijeme prijenosa signala je 24 ms,
— relej u TS Vinčent prima signal 5 ms nakon nastanka kvara i izdaje nalog za isklop prekidača. Vrijeme prijenosa signala je 31 ms.

Prema analizi sustav zaštite i telekomunikacija za prijenos signala djelovali su zadovoljavajuće, te se zaključilo da se može pristupiti primarnim pokusima.

6 STVARNI DVOPOLNI KRATKI SPOJ NA T SPOJU

Nekoliko dana nakon sekundarnih ispitivanja s kraja na kraj grmljavinsko nevrijeme uzrokovalo je dvopolni kvar (L1-L2). Sustav zaštite i telekomunikacija nije djelovao ispravno. Lokacija kvara bila je takva da je relej u TE Plomin detektirao kvar u zoni 1 te je nakon 24 ms izdao nalog za isklop vlastitog prekidača i nalog za slanje signala za ubrzanje djelovanja prema preostala dva releja. Ostali releji detektirali su kvar u zoni pobude te su primili signal za ubrzano djelovanje.

Na osnovi zapisa iz numeričkog releja provedena je analiza. Relej u TS Šijana primio je signal 318 ms nakon nastanka kvara, a relej u TS Vinčent 428 ms. Prijenos signala u ovom slučaju trajao je 294 ms do TS Šijana, odnosno 404 ms do TS Vinčent. Kašnjenje u prijenosu signala uzrokovalo je definitivni isklop voda u TS Šijana i TS Vinčent. Na slici 9 prikazani su analogni i digitalni signali iz releja u TE Plomin i TS Vinčent.

detected a fault in zone $1(Z_1)$ and the relays of the Vinčent and Šijana substations in zone $2(Z_2)$. The relay at the Plomin TPP acted without a delay in time, and the other two relays acted after the receipt of the signal for accelerating the effect (without accelerated functioning, there would have occurred a delay in time of 500 ms). After the analysis of the records of the numerical relays, the following conclusion can be made:

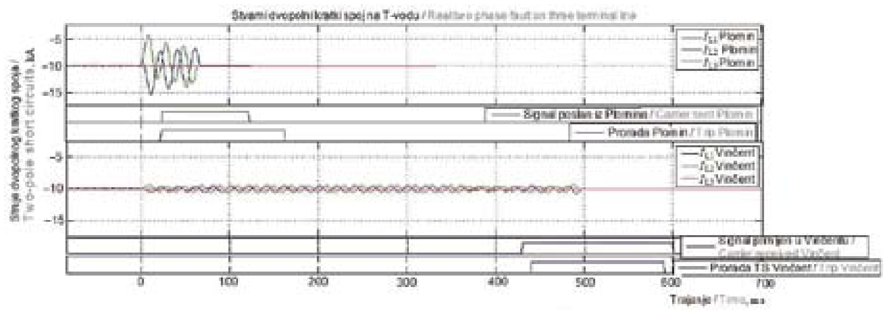
— the Plomin TPP relay issues the order for switch-off 24 ms after the occurrence of the fault,
— based on the injected secondary dimensions, the relay calculated that the fault occurred at 15,7 km that is, 47,5 % of the length of the protected transmission line for the L1-E fault, and for the L1-L2 fault at 16,4 km, that is 49,6 %,
— the Plomin TPP relay issues the order for sending the signal for accelerated effect 24 ms after the occurrence of the fault,
— the Šijana substation receives the signal 48 ms after the occurrence of the fault, Signal transmission time is 24 ms,
— the Vinčent substation receives the signal 5 ms after the occurrence of the fault and issues the order for switch-off of the breaker. Signal transmission time is 31 ms.

According to the analysis, the protection and telecommunication system for signal transmission acted satisfactorily and the conclusion was that primary trials can be started.

6 REAL TWO-POLE SHORT CIRCUIT AT THE T-JUNCTION

A few days after the secondary end-to-end trials, stormy weather conditions caused a two-pole fault (L1-L2). The protection and telecommunications system did not work properly. The location of the fault was such that the relay at the Plomin TPP detected a fault in zone 1 and after 24 ms issued an order for switch-off of its own breaker and an order for sending the signal for accelerated effect towards the other two relays. The other relays detected a fault in the actuation zone and received a signal for accelerated effect.

Based on the records from the numerical relay, an analysis was performed. The Šijana substation relay received a signal 318 ms and the Vinčent substation 428 ms after the occurrence of the fault. The signal transmission in this case took 294 ms to the Šijana substation, that is, 404 ms to the Vinčent substation. The delay in signal transmission caused a definite switch-off of the transmission line at the Šijana and Vinčent substations. Figure 9 shows analogous and digital signals from the relay at the Plomin TPP and the Vinčent substation.



Slika 9 — Podaci iz releja za dvopolni kratki spoj na stupu 49 T voda
Figure 9 — Data from the relay for the two-pole short circuit on pole 49 of the T-line

Nakon analize djelovanja sustava zaštite zaključeno je sljedeće:

- snaga analognog signala kojeg komunikacijski uređaji razmjenjuju radi nadzora veze podešena je na 12 dB. Podešena vrijednost može varirati ±1 dB,
- drugi komunikacijski uređaj pretvara taj signal u digitalni i šalje ga prema drugom kraju voda,
- snaga analognog signala koji se šalje kao kriterij za ubrzanje djelovanja podešena je na 5 dB,
- dozvoljena snaga signala koji se pretvara iz analognog u digitalni je 4 dB. Signal koji prijeđe podešenu vrijednost postaje izobličen,
- na osnovi zapisa iz numeričkih releja vidljivo je da je prijenos signala obavljen s velikim kašnjenjem,
- analiza je pokazala da je signal za ubrzanje (podešene snage 5 dB) prešao podešeni limit od 4 dB, te je na taj način postao izobličen. Pojačanje signala moglo je nastati zbog povećanja potencijala, različitih rezonancija, itd.,
- takav izobličeni signal pretvoren je u digitalni i putem digitalne mreže poslan prema ostalim relejima,
- temeljem iskustva može se zaključiti da takav signal nije imao zadovoljavajući format,
- pretvaranje takvog digitalnog signala u analogni uzrokovalo je kašnjenje u prijenosu signala.

Sukladno zaključcima analize podešeni su parametri komunikacijskog sustava kako slijedi:

- snaga signala za provjeru veze između konvertera je bila podešena na 6 dB,
- snaga signala za ubrzanje djelovanja ostala je 5 dB,
- dozvoljena snaga signala koji se pretvara iz analognog u digitalni podešena je na 0 dB.

After the analysis of the protection system effect, the following conclusion was made:

- the power of the analogous signal exchanged by the communication devices for the purpose of supervision of the connection is set at 12 dB. The set value can vary by ±1 dB,
- the other communication device turns that signal into a digital signal and sends it to the other end of the line,
- the power of the analogous signal sent as a criterion for accelerated effect, is set at 5 dB,
- the allowed power of the signal which changes from analogous to digital is 4 dB. The signal which exceeds the set value becomes deformed,
- based on the records from the numerical relays, it is evident that the transmission of the signal happened with a significant delay,
- analysis has shown that the signal for acceleration (power set at 5 dB) exceeded the set limit of 4 dB and thus became deformed. Strengthening the signal could have occurred due to increased potential, different resonances, etc.
- such a deformed signal was transformed into a digital signal and sent through the digital network to the other relays,
- experience points to the conclusion that such a signal was of unsatisfactory format,
- transformation of such a digital signal into an analogous signal caused the delay in the transmission of the signal.

According to the conclusions of the analyses, the parameters of the communication system were set as follows:

- the power of the signal for checking the connection between the converter was set at 6 dB,
- the power of the signal for accelerated effect remained at 5 dB,
- the allowed power of the signal which transforms from analogous to digital is set at 0 dB.

Neuspjeli otklon kvara za vrijeme dok je vod bio u pogonu pokazao je potrebu primarnog ispitivanja.

Unsuccessful fault removal while the transmission lines were operative, pointed to the need for primary trial.

7 PRIMARNO ISPITIVANJE

Nakon promjene parametara u komunikacijskom sustavu pristupilo se provedbi primarnih pokusa. Primarni pokusi provedeni su na stupu 49 na odvojku od TE Plomin do točke čvorišta (49,46 %, 16,234 km). Zbog rasporeda vodiča na stupu, slika 10, provedeni su pokusi L1-E i L1-L2.

7 PRIMARY TRIAL

After the change of the parameters in the communication system, the performance of primary trials was initiated. Primary trials were performed on tower number 49 on the extension from the Plomin thermal power plant to the hub point (49,46 %, 16,234 km). Because of the arrangement of the conductors on the tower, Figure 10, tests L1-E and L1-L2 were performed.

Slika 10 — Raspored vodiča na 49-om stupu
Figure 10 — Arrangement of the conductors on the 49th tower

Prije provedbe pokusa vod je bio izvan pogona, bakrena žica presjeka 1 m² pričvršćena je za fazu L2 i odmaknuta od voda izolatorskom trakom. Nakon toga vod se uključuje, izolatorska traka se presijeca i žica pada na konzolu stupa, što uzrokuje jednopolni kratki spoj između L1-E.

Na isti način provedena je priprema za dvopolni kvar, samo što je žica pričvršćena za fazu L1 te presijecanje izolatorske trake pada na fazu L2, što uzrokuje kvar (L1-L2).

7.1 Analiza jednopolnog kratkog spoja (L1-E)

Na temelju zapisa iz numeričkih releja, na slici 11 prikazane su analogne veličine i digitalni signali zabilježeni tijekom kvara L1-E. Referentne točke za vremensku analizu su početak i prestanak kvara:

— relej u TE Plomin izdaje nalog za isklop prekidača 28 ms nakon nastanka kvara, struja kvara nestaje nakon 63 ms,
— relej je izmjerio lokaciju do mjesta kvara 51,1 %, odnosno 16,9 km,
— pogreška u određivanju lokacije je +2,04 %,

Before the performance of the tests the power line was out of operation, the copper wire with the intersection of 1 m² was attached to L2 phase and detached from the power line by isolation tape. After that the transmission line is switched on, the isolation tape is cut and the wire falls on the tower console and this causes a short circuit between L1-E.

The preparation for the two-pole fault was performed in the same manner, but the wire was attached to L1 phase and the cutting of the isolation tape fell onto L2 phase which caused the fault (L1-L2).

7.1 Analysis of the one-pole short-circuit (L1-E)

Based on the records from the numerical relays, Figure 11 shows analogous dimensions and digital signals recorded during the L1-E fault. The reference points for temporal analysis are the beginning and the end of the fault:

— the Plomin TPP relay issues the order for breaker switch-off 28 ms after the occurrence of the fault, and the fault current occurs after 63 ms,
— the relay measured the distance to the fault location of 51,1 %, that is, 16,9 km,

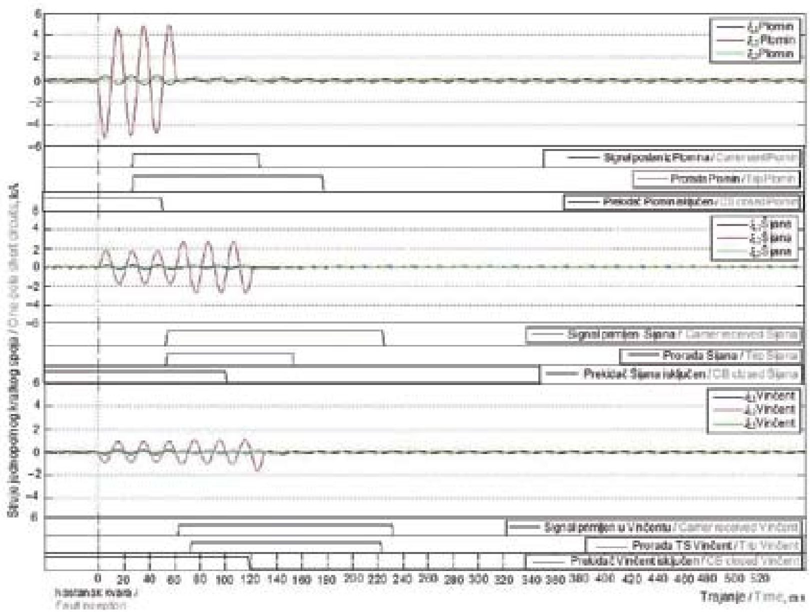
odnosno 0,67 km,

— relej u TS Šijana detektirao je kvar u zoni $2(Z_2)$, primio signal za ubrzanje djelovanja 54 ms nakon nastanka kvara te nakon toga izdao nalog za isključenje. Prijenos signala trajao je 26 ms. Struja kvara nestaje nakon 122 ms,
— relej u TS Vinčent detektirao je kvar u zoni $2(Z_2)$, primio je signal za ubrzanje 65 ms nakon nastanka kvara te nakon toga izdao nalog za isključenja. Prijenos signala trajalo je 37 ms. Struja kvara prestaje nakon 133 ms,
— 65 ms nakon nastanka kvara struja se povećava u TS Šijana i TS Vinčent. Razlog povećanja je isključenje prekidača u TE Plomin pa se kvar napaja iz preostala dva kraja voda,
— 122 ms nakon nastanka kvara struja se povećava u TS Vinčent kao posljedica isključenja prekidača u TS Šijana. Kvar se napaja samo iz TS Vinčent,
— struja kvara potpuno nestaje 133 ms nakon isključenja prekidača u TS Vinčent,što je 70 ms nakon nestanka struje kvara u TE Plomin. Svi releji odradili su uspješno automatski ponovni uklop.

Trenutak uklopa prekidača nakon beznaponske pauze nije prikazan (beznaponska pauza podešena na 1,2 s), jer bi slika bila nepregledna.

— the error in location determination is +2,04 %, that is, 0,67 km,
— the Šijana substation relay detected a fault in zone $2(Z_2)$, received the signal for accelerated effect 54 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 26 ms. Fault current disappeared after 122 ms,
— the Vinčent substation relay detected a fault in zone $2(Z_2)$, received the signal for accelerated effect 65 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 37 ms. Fault current ends after 133 ms,
— 65 ms after the occurrence of the fault, the current increases at the Šijana and Vinčent substations. The reason for the increase is the switch-off of the Plomin TPP breaker so that the fault is charged from the other two line ends,
— 122 ms after the occurrence of the fault, the current increases at the Vinčent substation as a consequence of the switch-off of the breaker at the Šijana substation. The fault is charged only from the Vinčent substation.
— the fault current completely disappears 133 ms after the switch-off of the breaker at the Vinčent substation, and that is 70 ms after the disappearance of the fault current at the Plomin TPP. All the relays successfully performed automatic re-switch-on.

The moment of breaker switch-on after the voltage-free pause is not shown (voltage-free pause set at 1,2 s) because then the image could not be easily surveyed.



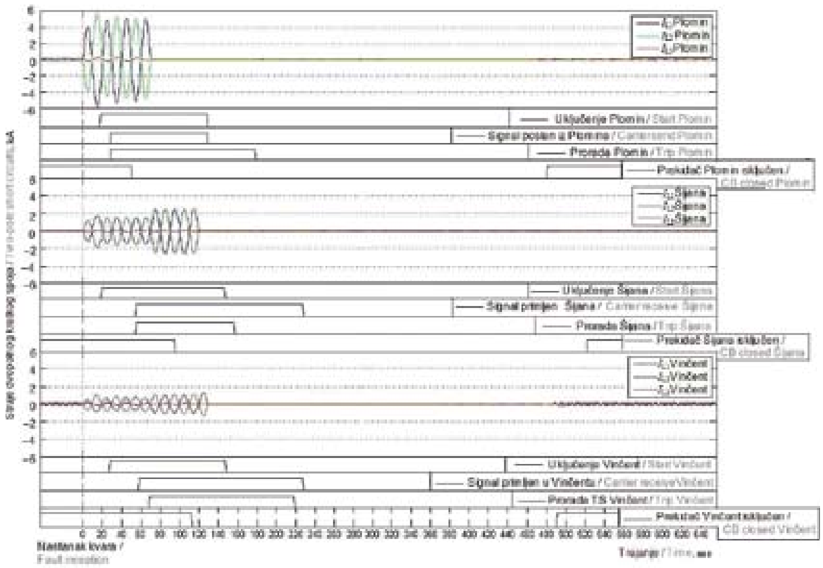
Slika 11 — Analogne i digitalne vrijednosti za vrijeme ispitivanja pomoću jednopolnog kratkog spoja (L1-E)
Figure 11 — Analogous and digital values during the trial by virtue of the one-pole short circuit (L1-E)

7.2 Analiza dvopolnog kratkog spoja L1-L2

Na temelju zapisa iz numeričkih releja na slici 12 prikazane su analogne veličine i digitalni signali zabilježeni tijekom kvara L1-L2. Slika 13 prikazuje paljenje luka za vrijeme kvara.

7.2 Analysis of the two-pole short-circuit L1-L2

Based on the records from the numerical relays, Figure 12 shows analogous values and digital signals recorded during the L1-L2. Figure 13 shows the ignition of the arch during the fault.



Slika 12 — Analogne i digitalne vrijednosti za vrijeme ispitivanja kod dvopolnog kratkog spoja (L1-L2)
Figure 12 — Analogous and digital values for the duration of the trial at a two-pole short circuit (L1-L2)

Slika 12 — Luk za vrijeme dvopolnog kratkog spoja (L1-L2) za vrijeme ispitivanja
Figure 12 — The arch during the two-pole short circuit (L1-L2) during the trial

Referentne točke za vremensku analizu su početak i prestanak kvara:

- relej u TE Plomin izdaje nalog za iskop prekidača 28 ms nakon nastanka kvara, struja kvara nestaje nakon 71 ms,
- relej je izmjerio lokaciju do mjesta kvara 47 %, odnosno 15,5 km,
- pogreška u određivanju lokacije je – 2,46 %, odnosno – 0,734 %,
- relej u TS Šijana detektirao je kvar u zoni 2(Z_2), primio je signal za ubrzanje djelovanja 54 ms nakon nastanka kvara, te nakon toga

The reference points for temporal analysis are the beginning and the end of the fault.

- the Plomin TPP relay issues the order for breaker switch-off 28 ms after the occurrence of the fault, and the fault current disappears after 71 ms,
- the relay measured the distance to the fault location at 47 %, that is, 15,5 km,
- the error in location determination is – 2,46 %-, that is, – 0,734 %,
- the Šijana substation relay detected a fault in zone 2(Z_2), received the signal for accelerated

izdao nalog za isključenje. Prijenos signala trajao je 26 ms. Struja kvara nestaje nakon 120 ms,

- relej u TS Vinčent detektirao je kvar u zoni $2(Z_2)$, primio je signal za ubrzanje 59 ms nakon nastanka kvara, te nakon toga izdao nalog za isključenja. Prijenos signala trajalo je 31 ms. Struja kvara prestaje nakon 130 ms,
- struja kvara potpuno nestaje 130 ms nakon isključenja prekidača u TS Vinčent, što je 59 ms nakon nestanka struje kvara u TE Plomin,
- relej u TE Plomin izdaje nalog za uklop prekidača 321 ms nakon nastanka kvara. Na temelju zapisa numeričkih releja prekidač je ponovno uključen 382 ms nakon nastanka kvara,
- relej u TS Šijana izdaje nalog za uklop prekidača 392 ms nakon nastanka kvara. Na temelju zapisa numeričkog releja prekidač je ponovno uključen 522 ms nakon nastanka kvara,
- relej u TS Vinčent izdaje nalog za ponovni uklop prekidača 378 ms nakon nastanka kvara. Na temelju zapisa numeričkog releja prekidač je ponovno uključen 490 ms nakon nastanka kvara,
- svi releji su ispravno odradili ciklus tropolnog automatskog ponovnog uklopa.

8 ANALIZA REZULTATA

Rezultati primarnih pokusa također su iskorišteni i za provjeru točnosti modela mreže pomoću CAPE sustava za zapadni dio EES-a Hrvatske. Simulirani kvarovi u mreži su iskorišteni za definiranje sekvenci end to end testiranja. Releji su se ponašali kako je i bilo predviđeno u simulaciji. Nakon primarnih ispitivanja zapisi iz releja su bili od velike koristi za određivanje točnosti modela budući da je topologija mreže i lokacija kvara poznata. Analiza rezultata je pokazala da su razlike između vrijednosti dobivenih simulacijom i onih koje su dobivene iz releja u zadovoljavajućim granicama. Valja napomenuti da je struja prije kvara podešena na vrijednost nula s obzirom da CAPE program ne podržava proračun tokova snaga. Osim toga, algoritam korišten za COMTRADE [5] ne podržava upravljanje prekidačem pa stoga simulirane struje kvara nisu mogle biti zaustavljene.

8.1 Usporedba rezultata za jednopolni kratki spoj (L1-E)

Usporedba rezultata dobivenih simulacijom za jednopolni kvar (L1-E) sa stvarnim rezultatima dobivenim iz zapisa releja prikazana je u tablici 4, a grafički na slici 14. Grafički prikaz simulacije je dobiven algoritmom iz CAPE programske podrš-

effect 54 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 26 ms. Fault current disappeared after 120 ms,

- the Vinčent substation relay detected a fault in zone $2(Z_2)$, received the signal for acceleration 59 ms after the occurrence of the fault, and after that issued the switch-off order. Duration of signal transmission was 31 ms. Fault current ended after 130 ms,
- the fault current completely disappears 130 ms after the switch-off of the breaker at the Vinčent substation, and that is 59 ms after the disappearance of the fault current at the Plomin TPP.
- the Plomin TPP relay issues the order for switch-on 321 ms after the occurrence of the fault, Based on the records of numerical relays, the breaker was switched on again 382 ms after the occurrence of the fault,
- the Šijana substation relay issues the order for breaker switch-on 392 ms after the occurrence of the fault, Based on the records of numerical relays, the breaker was switched on again 522 ms after the occurrence of the fault,
- the Vinčent substation relay issues the order for breaker re-switch-on 378 ms after the occurrence of the fault, Based on the records of numerical relays, the breaker was switched on again 490 ms after the occurrence of the fault,
- All the relays properly performed the three-pole automatic re-switch-on cycle.

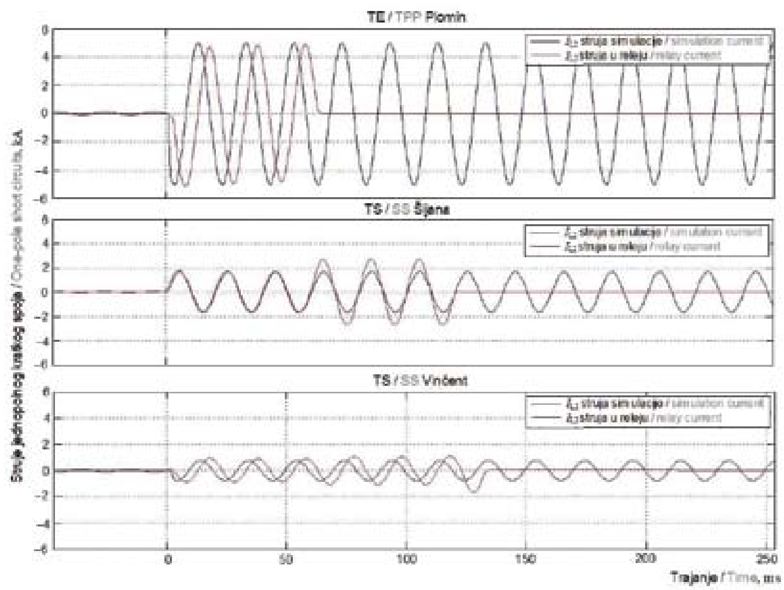
8 RESULT ANALYSIS

The results of primary trials were also used for the verification of the accuracy of the network model by virtue of the CAPE system for the western part of the Croatian electrical power system. Simulated faults in the network were used for defining the sequences of the end-to-end trial. The relays acted as was predicted in the simulation. After the primary trials, the relay records were highly helpful for the determination of the accuracy of the model as the topology of the network and the location of the fault were known. The analysis of the results showed that the differences between the values obtained by simulation and those obtained from the relays are within satisfactory limits. It needs to be pointed out that the current before the fault was set at zero considering the fact that the CAPE programme does not support the estimation of power flows. Besides that, the algorithm used for COMTRADE [5] did not support the operation of the breaker so the simulated current faults could not be stopped.

8.1 Comparison of results for the one-pole short circuit (L1-E)

The comparison of results obtained by virtue of simulation for the one-pole fault (L1-E) with real results obtained from the relay records is shown in Table 4 ke stvaranjem COMTRADE datoteka s kvarovima. Rezultati su zatim obrađeni u MATLAB-u i uspoređeni sa zapisima iz releja.

and graphically in Figure 14. The graphic presentation of the simulation was obtained by virtue of the algorithm from the CAPE programme support by creating the COMTRADE fault files. Results were then analysed in MATLAB and compared with the relay records.



Slika 14 — Usporedba struja izmjerenih u releju i simulaciji za vrijeme jednopolnog kratkog spoja (L1-N)
Figure 14 — Comparison of currents measured in the relay and in the simulation during the one-pole short circuit (L1-N)

Razlike između vrijednosti dobivenih simulacijom i stvarnih vrijednosti su zadovoljavajuće za TE Plomin i TS Šijanu, dok je najveće odstupanje za TS Vinčent, 21 %.

The differences between the values obtained by simulation and the real values are satisfactory for the Plomin TPP and the Šijana substation while the greatest deviation occurred for the Vinčent substation, 21 %.

Tablica 4 – Usporedba rezultata za jednopolni kratki spoj (L1-E) za fazu u kvaru
Table 4 – Comparison of results for the one-pole short circuit (L1-E) for the phase at fault

		Zapis iz releja / Relay records		CAPE simulacija / CAPE simulation		Razlika / Difference , %
		Iznos / Value	Kut / Angle, °	Iznos / Value	Kut / Angle, °	
Plomin	I_{L1}	3,45 kA	102,8	3,59 kA	158,4	4,0
	V_{L1}	63,5 kV	67,2	59,7 kV	–60.0	5,9
Šijana	I_{L1}	1,24 kA	–44,4	1,35 kA	162,0	8,8
	V_{L1}	32,9 kV	24,8	32,3 kV	–120,0	1,8
Vinčent	I_{L1}	0,71 kA	–14,67	0,56 kA	163,0	21,0
	V_{L1}	36,9 kV	–74,8	32,2 kV	119,2	12,7

Na slici 14 valja obratiti pozornost na povećanje struje releja. To se javlja iz razloga upravljanja prekidačem u TE Plomin i promjene toka struje u mreži [6]. Slično kao i u slučaju usporedbe TS Šijana, za relej u TS Vinčent struja ima jednu vrijednost u trenutku nastanka kvara i ta vrijednost raste kada relej u Plominu proradi. Konačni porast struje nastaje zbog prorade releja u TS Šijana.

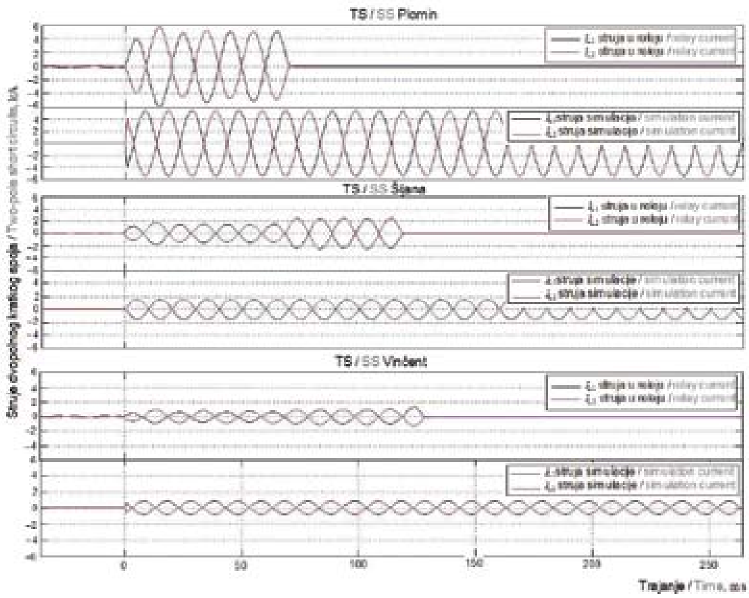
As regards Figure 14, attention should be paid to the increased relay current. That happens because of the operation of the breaker at the Plomin TPP and because of the change of the current flow in the network [6]. Similarly to the case of comparison for the Šijana substation, the current for the Vinčent substation relay is at a certain value at the moment of fault occurrence and that value increases when the relay in Plomin trips. The final current increase occurs due to the Šijana relay trip.

8.2 Usporedba rezultata za dvopolni kratki spoj (L1-L2)

Usporedba rezultata dobivenih simulacijom za dvopolni kvar (L1-L2) sa stvarnim rezultatima dobivenim iz zapisa releja prikazana je u tablici 5 i grafički na slici 15. Grafički prikaz simulacije je dobiven algoritmom iz CAPE programske podrške stvaranjem COMTRADE datoteka sa kvarovima. Rezultati su zatim obrađeni u MATLAB-u i uspoređeni sa zapisima iz releja.

8.2 Comparison of results for the two-pole short circuit (L1-L2)

The comparison of results obtained by virtue of simulation for the two-pole fault (L1-L2) with real results obtained from the relay records is shown in Table 5 and graphically in Figure 15. The graphic presentation of the simulation was obtained by virtue of the algorithm from the CAPE programme support by creating the COMTRADE fault files. Results were then analysed in MATLAB and compared with the relay records.



Slika 15 — Usporedba struja izmjerenih u releju i simulaciji za vrijeme dvopolnog kratkog spoja (L1-L2)
Figure 15 — Comparison of currents measured in the relay and in the simulation during the two-pole short circuit (L1-L2)

Razlike za dvopolni kratki spoj nešto su veće, ali još uvijek zadovoljavaju kriterije točnosti modela. Najveća razlika se javlja kod releja u TS Šijana, i iznosi 19,2 %. Najveća naponska razlika je kod releja u TS Vinčent i iznosi 12 %.

Na temelju rezultata dobivenih analizom nakon provedenih primarnih pokusa može se zaključiti da releji proračuju u skladu sa zahtjevima pogona elektroenergetskog sustava [7] i [8]. Točnost modela je zadovoljavajuća pa se podaci dobiveni simulacijama kvarova mogu koristiti prilikom određivanja podešenja za pojedine releje.

9 ZAKLJUČAK

Pokazano je da sekundarno testiranje releja ponekad nije dovoljno da se dobije uvid u funkcionalnost sustava zaštite. Provedenim ispitivanjem s kraja na kraj zaključeno je da sustav zaštite djeluje ispravno.

The differences for the two-pole short circuit are somewhat greater but still satisfy the criteria of model accuracy. The greatest difference occurs at the relays in the Šijana substation and it amounts to 19,2 %. The greatest voltage difference occurs at the relays at the Vinčent substation and it amounts to 12 %.

Based on the results obtained by the analysis after the performance of primary trials, the conclusion can be drawn that the relays trip in accordance with the requests of the electrical power system drives [7] and [8]. The accuracy of the model is satisfactory because the data obtained by simulation of faults can be used when determining the settings for certain relays.

9 CONCLUSION

The presented secondary testing of the relays is sometimes not sufficient for gaining an insight into the functionality of the protection system. The performed end-to-end trial gives rise to the conclusion that the protection system works properly.

Tablica 5 – Usporedba rezultata za dvopolni kratki spoj (L1-L2) za fazu u kvaru
Table 5 – Comparison of results for the two-pole short circuit (L1-L2) for the phase at fault

		Zapis iz releja / Relay records		CAPE simulacija / CAPE simulation		Razlika / Difference, %
		Iznos / Value	Kut / Angle , °	Iznos / Value	Kut / Angle, °	
Plomin	I_{L1}	3,88 kA	−30,4	3,47 kA	−51,9	10,5
	I_{L2}	3,75 kA	150,4	3,47 kA	128,1	7,3
	V_{L1}	42,0 kV	−10,7	39,6 kV	−22,8	5,6
	V_{L2}	41,6 kV	−83,3	40,0 kV	−96,8	3,8
Šijana	I_{L1}	1,04 kA	166,5	1,24 kA	−47,0	19,2
	I_{L2}	1,08 kA	−15,7	1,24 kA	132,0	14,8
	V_{L1}	37,2 kV	172,0	36,7 kV	−164,0	1,3
	V_{L2}	35,8 kV	119,4	38,1 kV	−89,1	6,4
Vinčent	I_{L1}	0,52 kA	158,3	0,55 kA	−47,0	7,1
	I_{L2}	0,61 kA	−25,2	0,55 kA	133,0	5,3
	V_{L1}	37,5 kV	166,8	33,0 kV	−29,2	12,0
	V_{L2}	36,5 kV	109,7	39,3 kV	−89,6	7,8

Nakon predpodešenja parametara komunikacijskog sustava provedbom primarnih pokusa ispitano je djelovanje releja u okruženju u kojem oni moraju raditi prilikom pojave kvara na štićenom objektu.

Naknadnom analizom zaključeno je da su releji i sustav komunikacije ispravno djelovali. Unatoč korištenju dva komunikacijska pretvornika i digitalne mreže kao medija za prijenos signala za djelovanje zaštite, kašnjenje u prijenosu signala je bilo manje od 40 ms.
Nesinkronizirani isklopi i uklopi prekidača nisu uzrokovali nestabilnosti unutar elektroenergetskog sustava, što navodi na zaključak da ovakav sustav zaštite udovoljava kriterijima sigurnog pogona.

Usporedbom analognih vrijednosti struja i napona dobivenih simulacijom pomoću CAPE programske podrške i vrijednosti koje je zabilježio relej tijekom primarnog testiranja na 49-om stupu pokazuju da je matematički model elektroenergetske mreže na kojoj je izvedena simulacija dobro dizajniran. Razlike u vrijednostima su u prihvatljivim granicama od 3,8 % do 10,5 % za TE Plomin, 1,3 % do 19 % za TS Šijana i 5,3 % do 21 % za TS Vinčent. Zaključak je da su ulazni podaci za sekundarno ispitivanje bili dobri.

Sekundarno ispitivanje na vodu Plomin – Šijana – Vinčent je pokazalo da takvi testovi ponekada nisu dovoljni kako bi se dobili relevantni podaci pomoću kojih se može jamčiti puna zaštita štićenog objekta. Ispitivanje provedeno sekundarnim injektiranjem analognih vrijednosti (ispitivanje s kraja na kraj) pokazalo je da sustav radi ispravno, ali tijekom pravog kvara pokazalo se da ipak nije

After the pre-setting of the parameters of the communication system by performing primary trials, the functioning of the relays in an environment in which these must operate at the instance of occurrence of a fault in the protected facility was tested.

Subsequent analysis resulted in the conclusion that the relays and the communication system worked properly. Although two communication converters and the digital network as the medium for the transmission of the signal for the protection functioning were used, the delay in signal transmission was less than 40 ms.
Unsynchronised breaker switch-offs and switch-ons did not cause instabilities within the electrical power system which gives rise to the conclusion that such a protection system meets safe operation criteria.

The comparison of analogous values of currents and voltages obtained by simulation by virtue of the CAPE programme support and the values recorded by the relay during the primary trial at the 49th tower, show that the mathematical model of the electrical power network, which was subjected to the simulation, was well designed. The differences in the values are within acceptable limits of 3,8 % up to 10,5 % for the Plomin TPP, 1,3 % up to 19 % for the Šijana substation, and 5,3 % do 21 % for the Vinčent substation. The conclusion is that input data for the secondary trial were right.

The secondary trial at the Plomin – Šijana – Vinčent transmission line showed that such tests are sometimes not sufficient to get relevant data which can guarantee full safety of the protected facility. The trials performed by secondary injection of analogous values (end-to-end trial) showed that the system works properly but during the real fault it was revealed that it is nevertheless not completely satispotpuno zadovoljavajuće, jer ulazne vrijednosti potrebne za ispitivanje (naponi i struje) nisu bile jednake vrijednostima koje su se javile tijekom pravog kvara.

Nakon predpodešenja parametara komunikacijskog sustava provedbom primarnih pokusa ispitano je djelovanje releja u okruženju u kojem oni moraju raditi prilikom pojave kvara na štićenom objektu.

Na promatranom vodu se nakon ispitivanja javilo nekoliko kvarova i zaštita je ispravno proradila u svakom slučaju.

Ovakav sustav zaštite najviše ovisi o dostupnosti i pouzdanosti telekomunikacijskog sustava pa valja napomenuti da se sustav zaštite u ovom slučaju ne može razmatrati neovisno od sustava komunikacije, već sve treba sagledavati kao jedinstvenu cjelinu.

factory because input values necessary for the trial (voltages and currents) were not equal to the values which occurred during the real fault.

After the pre-setting of the parameters of the communication system by implementing primary trials, the functioning of the relays in an environment in which these must operate at the instance of occurrence of a fault in the protected facility was tested.

After the trial, several faults occurred on the observed transmission line and the protection tripped properly at every instance.

This kind of protection system depends mostly on the availability and the reliability of the telecommunication system so it needs to be stressed that the protection system in this case cannot be observed separately from the communication system but that the entire issue needs to be observed as a unique whole.

LITERATURA / REFERENCES

[1] ALEXANDER, G.E., ANDRICHAK, J.G., Application of Phase and Ground Distance Relays to Three Terminal Lines, GE Protection and Control, Malvern, PA, GE – 3964
[2] CIGRE SC34 WG34/35.11, Protection Using Telecommunications, 2000
[3] CAPE Short Circuit Tutorial, Electrocon International, Inc., May 2000
[4] CAPE Coordination Graphics Tutorial, Electrocon International, Inc., April 2000
[5] IEEE Standard Common Format for Transient Data Exchange (COMTRADE), for Power Systems, IEEE C37.111-1999
[6] FRLAN,K., Analysis of Influence of Intermediate In-feeds and Fault Resistance Upon Distance Protection Functionality, Master Thesis, Faculty of Electrical Engineering and Computing, University of Zagreb, Zagreb, 2006
[7] FRLAN, K., RUBEŠA, R., MARUŠIĆ, A., Influence of New Over-head Power Lines on the Operation of the Relay Protection System, IEEE, Africon 2007, Windhoek, Namibia, 2007
[8] RUBEŠA, R., FRLAN, K., MARUŠIĆ, A., Influence of Fault Resistance on the Operation of Relay Protection Before and After the Construction of New Lines, European Power and Energy Systems, Europes 2007, August 2007, Palma de Mallorca, Spain

Adresa autora:

Mr. sc. **Kristijan Frlan**
kristijan.frlan@hep.hr
HEP Operater prijenosnog Sustava d.o.o.
M. Tita 166, 51410 Opatija, Hrvatska
Prof. dr. sc. **Ante Marušić**
ante.marusic@fer.hr
Dr. sc. **Juraj Havelka**
juraj.havelka@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva
Unska 3, 10000 Zagreb, Hrvatska

Author's Adresses:

Kristijan Frlan, MSc
kristijan.frlan@hep.hr
HEP Operator prijenosnog sustava d.o.o.
M. Tita 166, 51410 Opatija, Croatia
Prof. **Ante Marušić**, PhD
ante.marusic@fer.hr
Juraj Havelka, PhD
juraj.havelka@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing
Unska 3, 10000 Zagreb,Croatia

Uredništvo primilo rukopis:
2009-05-09

Prihvaćeno:
2009-06-02

Manuscript received on:
2009-05-09

Accepted on:
2009-06-02

ANALIZA KUTNE STABILNOST SINKRONOG GENERATORA U OVISNOSTI O IZBORU SUSTAVA UZBUDE

ANALYSIS OF SYNCHRONOUS GENERATOR ANGULAR STABILITY DEPENDING ON THE CHOICE OF THE EXCITATION SYSTEM

Mato Mišković – Marija Mirošević – Mateo Milković,
Dubrovnik, Hrvatska

U radu je razvijen je matematički model elektroenergetskog sustava s više sinkronih generatora u kojemu su generatori predstavljeni nelinearnim matematičkim modelom. Primjenom takvog modela istražen je utjecaj načina napajanja sustava uzbude na kutnu stabilnost generatora u uvjetima pojave kratkog spoja u mreži. Postavljeni model omogućuje analizu stabilnosti generatora u uvjetima velikih poremećaja u elektroenergetskom sustavu za slučaj generatora s nezavisnom uzbudom i generatora sa samouzbudom. Rezultati istraživanja mogu poslužiti prilikom donošenja odluke o izboru tipa uzbude generatora, pri obnovi postojećih i izgradnji novih generatora.

The paper elaborates on the mathematical model of the electric power system with several synchronous generators and in this model the generators are presented by a non-linear mathematical model. By applying such a model, the impact of the manner of supplying the excitation system on the generator's angular stability was researched in the circumstances of occurrence of a short circuit in the network. The established model enables the analysis of the generator's stability in the circumstances of extensive disruptions in the electric power system for the case of the generator with separate excitation and the generator with self-excitation. Research results can be useful when making the decision on the choice of the generator excitation type, when renewing the existing and building new generators.

Ključne riječi: samouzbudni sustav; sinkroni generator; sustav nezavisne uzbude; višestrojni sustav
Key words: multiple-machine system; self-excitation system; separate excitation system; synchronous generator

1 UVOD

Suvremena tehnička rješenja sustava uzbude sinkronih generatora, gdje se uzbudni namot generatora napaja preko klizno-kolutnog sustava, izvode se kao samouzbudni sustavi i sustavi s nezavisnom uzbudom. Uzbudnik samouzbudnog sustava napaja se s izvoda glavnog generatora preko uzbudnog transformatora. Uzbudnik sustava s nezavisnom uzbudom napaja se iz posebnog izvora, kod malih generatora to je najčešće generator s permanentnim magnetima, a kod većih generatora to je uzbudni sinkroni generator koji se nalazi na zajedničkoj osovini s glavnim generatorom.

Neovisno o načinu napajanja, uzbudnik se u pravilu izvodi kao punoupravljivi ispravljač u mosnom spoju.

Suvremeni regulatori napona sinkronog generatora izvode se kao digitalni mikroprocesorski regulatori s klasičnim i naprednim algoritmima i funkcijama. Važno je napomenuti da nema bitne razlike u strukturi regulatora napona za sustav s nezavisnom uzbudom i samouzbudni sustav.

Osnovna razlika među njima proizlazi iz ponašanja u pogonu pri kratkim spojevima u prijenosnoj mreži. Kod generatora s nezavisnim sustavom uzbude kratki spoj u mreži ne rezultira smanjenjem napona uzbude generatora.

Kod samouzbudnog sustava, prilikom pojave kratkog spoja u mreži, dolazi do pada napona generatora, a time i do smanjenja napona napajanja uzbude. Pri dugotrajnim kratkim spojevima, zbog pada napona uzbude, značajnije se smanjuje magnetski tok ulančen uzbudnim namotom, zbog čega se smanjuje i sinkronizacijski moment generatora. Kako se može pretpostaviti, snaga pogonskog stroja je stalna, što rezultira porastom brzine vrtnje i kuta opterećenja, a u određenim situacijama može doći i do ispada generatora iz mreže.

U ovom radu analizira se kutna stabilnost generatora/agregata sa samouzbudnim i sustavom s nezavisnom uzbudom u uvjetima pojave kratkog spoja u prijenosnoj mreži. Za odabranu prijenosnu mrežu (slika 1), koja je dio elektroenergetskog sustava (EES) u kojem se nalazi i HE Dubrovniku, provedeni su proračuni kuta opterećenja generatora pri pojavi kratkog spoja u mreži. Promatra se kut između vektora napona E'_q i vektora napona krute mreže U_m.
Proračuni su učinjeni za dva različita mjesta nastanka i za različita vremena trajanja kratkog spoja. Za potrebe analize odabran je odziv kuta

1 INTRODUCTION

Modern technical solutions regarding synchronous generator excitation systems, in case when the generator's excitation winding is supplied through the sliding ring system, are designed as self-excitation systems and separate excitation systems. The exciter of the self-excitation system is supplied from the lead of the main generator through the excitation transformer. The exciter of the separate excitation system is supplied from a special source; in case of small generators, this is most often a generator with permanent magnets and in case of bigger generators, it is an excitation synchronous generator located on the axis common with the main generator.

Regardless of the manner of supply, the exciter is normally designed as a fully-three phase full controlled bridge rectifier.

Modern synchronous generator voltage regulators are designed as digital microprocessor regulators with classical and advanced algorithms and functions. It is important to mention that no significant difference exists between the structure of the voltage regulator for the system with separate excitation, and that of the self-excitation system.

The basic difference between them arises from the behaviour in operation at short circuits in the transmission network. In the separate excitation system generators, a short circuit in the network does not result in the reduction of the generator excitation voltage.

In the self-excitation system, when a short circuit occurs in the network, there occurs a reduction in the generator voltage, and thus also a reduced excitation supply voltage. Upon long-lasting short circuits, due to the reduced excitation voltage, the magnetic flux chained by the excitation winding decreases more significantly and therefore the generator synchronization moment decreases as well. As can be assumed, the power of the drive engine is constant, which results in an increase of the rotation speed and the load angle and, in certain cases, generator's outage from the network can also occur.

The paper presents the angular stability of the generator/aggregate with the self-excitation and the separate excitation system in the circumstances of occurrence of a short circuit in the transmission network. For the selected transmission network (Figure 1), which is part of the electric power system (PS) in which the HPP Dubrovnik is located as well, calculations of the generator load angles have been performed at the occurrence of a short circuit in the network. The angle between the voltage vector E'_q and the infinite network voltage vector U_m was observed.

opterećenja jer on daje izravnu informaciju o dinamičkoj stabilnosti sinkronoga generatora pri poremećajima u elektroenergetskom sustavu.

2 MODELIRANJE ELEKTROENERGETSKOG SUSTAVA

Za analizu stabilnosti samouzbudnog sustava i sustava s nezavisnom uzbudom u uvjetima pojave kratkog spoja u prijenosnoj mreži načinjen je EES koji obuhvaća:

- matematički model sinkronog generatora u paralelnom radu u mreži,
- matematički model nezavisnog i samouzbudnog sustava uzbude i
- matematički model prijenosne mreže.

Prijenosna mreža modelirana je sustavom algebarskih jednadžbi u kojima su struje i naponi dani kao fazorske veličine, dok je sinkroni generator modeliran u vremenskom području sa sustavom diferencijalnih jednadžbi prema [1].

2.1 Matematički model sinkronog generatora

Nelinearni matematički model sinkronog generatora trećeg reda u dq-sustavu izveden je prema [2], [3] i [4] i prilagođen za simulacijske proračune. Odabrane ulazne veličine su: napon uzbude e, moment pogonskog stroja m_t i napon mreže U_m, dok su izlazne veličine: napon generatora U_G, struja generatora I_G, električka snaga P i kut opterećenja δ:

The calculations were performed for two different places of occurrence and for different time of duration of the short circuit. For the needs of the analysis, the response of the load angle was chosen because it provides direct information on the dynamic stability of the synchronous generator upon the disruptions in the electric power system

2 MODELLING THE ELECTRIC POWER SYSTEM

For the analysis of the stability of the self-excitation system and the separate excitation system in the circumstances of occurrence of a short circuit in the transmission network, an PS was generated which includes:

- the synchronous generator mathematical model in parallel operation in the network,
- the mathematical model of the separate and self-excitation systems, and
- the mathematical model of the transmission network.

The transmission network is modelled by a system of algebraic equations in which the currents and the voltages are given as phasor, while the synchronous generator is modelled in a time domain with a differential equations system according to [1].

2.1 Mathematical model of the synchronous generator

The non-linear mathematical model of the synchronous generator of the third order in the dq-system is designed according to [2], [3] and [4] and adjusted for calculations. The selected input values are: excitation voltage e, drive engine moment m_t and network voltage U_m while output values are: generator voltage U_G, generator current I_G, electric power P and load angle δ:

$$\frac{\mathrm{d}\Psi_\mathrm{f}}{\mathrm{d}t} = \frac{\omega_\mathrm{s} r_\mathrm{f}(x_\mathrm{d} - x_\ell) U_\mathrm{m}\cos(\delta)}{\omega x'_\mathrm{d} x_\mathrm{f}} + \frac{\omega_\mathrm{s} r_\mathrm{f} e}{x_\mathrm{ad}} - \frac{\omega_\mathrm{s} r_\mathrm{f}(x_\mathrm{d} + x_\mathrm{m})\Psi_\mathrm{f}}{(x'_\mathrm{d} + x_\mathrm{m}) x_\mathrm{f}}, \quad (1)$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{T_\mathrm{m}}\left(m_\mathrm{t} - \left(\frac{\Psi_\mathrm{f} U_\mathrm{m}(x_\mathrm{d} - x_1)\sin(\delta)}{\omega(x'_\mathrm{d} + x_\mathrm{m}) x_\mathrm{f}} + \frac{U_\mathrm{m}^2 (x'_\mathrm{d} - x'_\mathrm{q})\sin(2\delta)}{2\omega^2 (x'_\mathrm{d} + x_\mathrm{m})(x'_\mathrm{q} + x_\mathrm{m})} \right) \right) - D(\omega - 1), \quad (2)$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega_\mathrm{s}(\omega - 1) . \quad (3)$$

Ovisnost ulančenih tokova u d-osi i q-osi o naponu krute mreže:

The dependency of the chained flows in the d-axis and q-axis on the infinite network voltage:

$$U_{\mathrm{m}} \cos(\delta) = \omega\psi_{\mathrm{d}} \quad , \tag{4}$$

$$U_{\mathrm{m}} \sin(\delta) = -\omega\psi_{\mathrm{q}} \quad . \tag{5}$$

Sustav algebarskih jednadžbi napona, struje i djelatne snage generatora je:

The system of algebraic voltage equations, the current and active power of the generator is:

$$U_{\mathrm{d}} = \frac{x_{\mathrm{q}} U_{\mathrm{m}} \sin(\delta)}{x_{\mathrm{q}} + x_{\mathrm{m}}} \quad , \tag{6}$$

$$U_{\mathrm{q}} = \frac{x_{\mathrm{d}}^{'} U_{\mathrm{m}} \cos(\delta)}{x_{\mathrm{d}}^{'} + x_{\mathrm{m}}} + \omega \mathrm{x}_{\mathrm{m}} (x_{\mathrm{d}} - x_{1}) \frac{\psi_{\mathrm{f}}}{\left(x_{\mathrm{d}}^{'} + x_{\mathrm{m}}\right) x_{\mathrm{f}}} \quad , \tag{7}$$

$$U_{\mathrm{G}} = \sqrt{U_{\mathrm{d}}^{2} + U_{\mathrm{q}}^{2}} \quad , \tag{8}$$

$$i_{\mathrm{q}} = \frac{U_{\mathrm{m}} \sin(\delta)}{\omega x_{\mathrm{m}}} - \frac{U_{\mathrm{d}}}{\omega x_{\mathrm{m}}} \quad , \tag{9}$$

$$i_{\mathrm{d}} = \frac{U_{\mathrm{q}}}{\omega x_{\mathrm{m}}} - \frac{U_{\mathrm{m}}}{\omega x_{\mathrm{m}}} \cos(\delta) \quad , \tag{10}$$

$$I_{\mathrm{G}} = \sqrt{I_{\mathrm{d}}^{2} + I_{\mathrm{q}}^{2}} \quad , \tag{11}$$

$$P = U_{\mathrm{d}} \cdot i_{\mathrm{d}} + U_{\mathrm{q}} \cdot i_{\mathrm{q}} \quad , \tag{12}$$

gdje su:

U_{m} – napon mreže,
Y_{f} – magnetski tok ulančen uzbudnim namotom,
Y_{d}, Y_{q} – ulančeni magnetski tokovi armature u d i q osi,
ω – kutna brzina,
ω_{s} – sinkrona brzina vrtnje generatora,
T_{m} – konstanta tromosti agregata,
D – koeficijent ekvivalentnog prigušenja,
x_{d} – uzdužna reaktancija armature,
x'_{d} – prijelazna uzdužna reaktancija armature,
x_{q} – poprečna reaktancija armature,
x_{m} – reaktancija do krute mreže,
r_{f} – djelatni otpor uzbudnog kruga,
x_{f} – reaktancija uzbudnog kruga,
U_{d}, U_{q} – komponente napona generatora u d-osi

whereat it is as follows:

U_{m} – network voltage,
Y_{f} – field flux linkages,
Y_{d}, Y_{q} – stator flux d and q-axis linkages,
ω – angular speed,
ω_{s} – base speed,
T_{m} – mechanical time constant,
D – damping coefficient,
x_{d} – synchronous d-axis reactance,
x'_{d} – d-axis transient reactance,
x_{q} – synchronous q-axis reactance,
x_{m} – reactance to the infinite network,
r_{f} – equivalent field winding resistance,
x_{f} – field winding reactance,
U_{d}, U_{q} – components of the generator voltage in the d-axis and the q-axis,
i_{d}, i_{q} – – armature current in d- axis and q-axis.

i q-osi,

i_d, i_q – komponente struje generatora u d-osi i q-osi

x_{ad} – reaktancija međuinduktivne veze armaturnog i uzbudnog namota u uzdužnoj osi,

x_l – rasipna reaktancija armature.

U simulacijskom proračunu, za rješavanje diferencijalnih jednadžbi (1), (2) i (3) korišten je prediktor-korektor postupak.

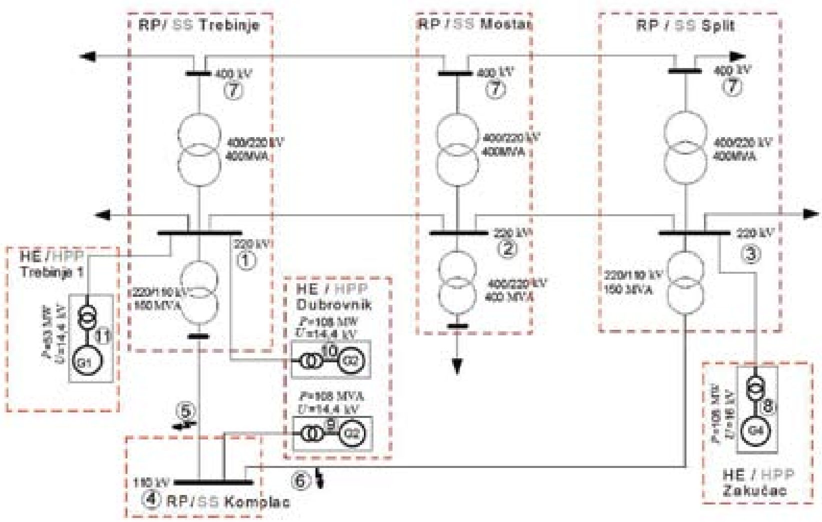
2.2 Matematički model prijenosne mreže

Matematički model je formiran za prijenosnu mrežu čija je jednopolna shema pokazana na slici 1. Mreža je dio elektroenergetskog sustava, a čine je: sinkroni generatori, transformatori, prijenosni vodovi i trošila.

In the calculations, for solving differential equations (1), (2) and (3), the predictor-corrector procedure was used.

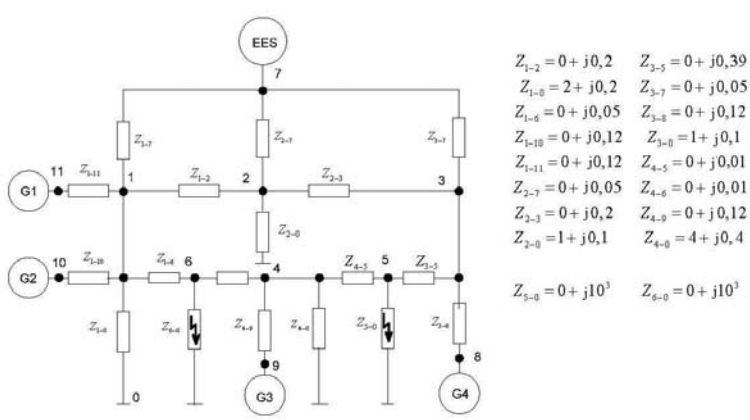
2.2 Mathematical model of the transmission network

The mathematical model is formed for the transmission network which single line diagram is shown in Figure 1. The network is part of the electric power system and it consists of: synchronous generators, transformers, transmission lines and power system devices.



Slika 1 — Jednopolna shema djela EES

Figure 1 — One-pole scheme of the part of the EPS



Slika 2 — Model elektroenergetskog sustava i vrijednosti pripadnih reaktancija

Figure 2 — Electric power system model and values of the pertaining reactance

Nadomjesna shema modelirane prijenosne mreže pokazana je na slici 2, vrijednosti nadomjesnih reaktancija su normirane na bazni sustav generatora 3 (G3). Ostatak elektroenergetskog sustava, koji je na promatrani sustav spojen prijenosnim vodom od $400\ \mathrm{kV}$, nadomješten je idealnim naponskim izvorom (EES). Na slici 2 trofazni sustav nadomješten je jednofaznim direktnim sustavom, što omogućava istraživanja simetričnih pojava. Za referentno čvorište odabrana je nultočka sustava.

Stanje u mreži opisuje se primjenom I Kirchoffovog zakona i za odabranu mrežu je:

The equivalent scheme of the modelled transmission network is shown in Figure 2, the values of equivalent reactance are set to the generator's basic system 3 (G3). The rest of the electric power system, which is connected to the observed system by a $400\ \mathrm{kV}$-transmission line, is substituted by an ideal voltage source (PS). In Figure 2, the three-phase system is substituted with a single-phase direct system which enables the research of symmetrical cases. The system's zero field was chosen as the reference node.

The situation in the network is described by applying the Kirchoff's Laws and for the selected network it is:

$$\begin{aligned}
&\frac{V_1}{Z_{1-2}}+\frac{V_1}{Z_{1-6}}+\frac{V_1}{Z_{1-7}}+\frac{V_1}{Z_{1-10}}+\frac{V_1}{Z_{1-11}}+\frac{V_1}{Z_{1-0}}-\frac{V_2}{Z_{1-2}}-\frac{V_6}{Z_{1-6}}-\frac{V_7}{Z_{1-7}}-\frac{V_{10}}{Z_{1-10}}-\frac{V_{11}}{Z_{1-11}}=0\\
&\frac{V_2}{Z_{1-2}}+\frac{V_2}{Z_{1-3}}+\frac{V_2}{Z_{1-7}}+\frac{V_2}{Z_{2-0}}-\frac{V_1}{Z_{1-2}}-\frac{V_3}{Z_{1-3}}-\frac{V_7}{Z_{1-7}}=0\\
&\frac{V_3}{Z_{2-3}}+\frac{V_3}{Z_{3-5}}+\frac{V_3}{Z_{3-7}}+\frac{V_8}{Z_{3-8}}-\frac{V_2}{Z_{2-3}}-\frac{V_5}{Z_{3-5}}-\frac{V_7}{Z_{3-7}}-\frac{V_8}{Z_{3-8}}=0\\
&\frac{V_4}{Z_{4-5}}+\frac{V_4}{Z_{4-6}}+\frac{V_4}{Z_{4-9}}+\frac{V_4}{Z_{4-0}}-\frac{V_5}{Z_{4-5}}-\frac{V_6}{Z_{4-6}}-\frac{V_9}{Z_{4-9}}=0\\
&\frac{V_5}{Z_{3-5}}+\frac{V_5}{Z_{4-5}}+\frac{V_5}{Z_{5-0}}-\frac{V_3}{Z_{3-5}}-\frac{V_4}{Z_{4-5}}=0\\
&\frac{V_6}{Z_{1-6}}+\frac{V_6}{Z_{4-6}}+\frac{V_6}{Z_{6-0}}-\frac{V_1}{Z_{1-6}}-\frac{V_4}{Z_{4-6}}=0
\end{aligned}\quad, \qquad (13)$$

gdje su čvorišta za koje su poznate vrijednosti napona:

where the nodes, for which the voltage values are known, are:

$$\begin{aligned}
&V_7=1+\mathrm{j}\cdot 0,\\
&V_8=U_{\mathrm{G4}}\cdot \mathrm{e}^{\mathrm{j}\varphi_7},\\
&V_9=U_{\mathrm{G3}}\cdot \mathrm{e}^{\mathrm{j}\varphi_8},\\
&V_{10}=U_{\mathrm{G2}}\cdot \mathrm{e}^{\mathrm{j}\varphi_9},\\
&V_{11}=U_{\mathrm{G1}}\cdot \mathrm{e}^{\mathrm{j}\varphi_{10}}.
\end{aligned} \qquad (14)$$

Sustav jednadžbi (13) u matričnom obliku je:

The equation system (13) in the matrix form is:

$$
\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \\ V_8 \\ V_9 \\ V_{10} \\ V_{11} \end{bmatrix}
=
\begin{bmatrix}
Y_{1,1} & 0 & 0 & 0 & 0 & Y_{1,6} & Y_{1,7} & 0 & 0 & Y_{1,10} & Y_{1,11} \\
Y_{2,1} & Y_{2,2} & Y_{2,3} & 0 & 0 & 0 & Y_{2,7} & 0 & 0 & 0 & 0 \\
0 & Y_{3,2} & Y_{3,3} & 0 & Y_{3,5} & 0 & 0 & Y_{3,8} & 0 & 0 & 0 \\
0 & 0 & 0 & Y_{4,4} & Y_{4,5} & Y_{4,6} & 0 & 0 & Y_{4,9} & 0 & 0 \\
0 & 0 & Y_{5,3} & Y_{5,4} & Y_{5,5} & 0 & 0 & 0 & 0 & 0 & 0 \\
Y_{6,1} & 0 & 0 & Y_{6,4} & 0 & Y_{6,6} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ U_{G4} \cdot e^{j\varphi_7} \\ U_{G3} \cdot e^{j\varphi_8} \\ U_{G2} \cdot e^{j\varphi_9} \\ U_{G1} \cdot e^{j\varphi_{10}} \end{bmatrix} . \tag{15}
$$

Matrica admitancija desno od znaka jednakosti u (15) formirana je iz (13) što odgovara metodi napona čvorova. Elementi na glavnoj dijagonali matrice određeni su sumom admitancija grana koje su povezane s i–tim čvorištem pa se općenito može napisati za čvorišta čiji potencijal nije poznat:

The admittance matrix right of the equation symbol in (15) is formed from (13) which matches the nodes voltage method. The elements on the main matrix diagonal are determined by the sum of the admittance of branches which are connected with the i-th node so, in general, for the nodes which potential is not known, the following can be written:

$$
Y_{i,i} = \sum_{i=1}^{n} \frac{1}{Z_{i,j}} \Bigg|_{(i=j)} , \tag{16}
$$

dok su vrijednosti ostalih elemenata čiji su potencijali poznati jednaki jedinici.

while the values of the other elements, which potentials are known, are equal to zero.

Članovi izvan glavne dijagonale matrice određuju se kao negativna vrijednost vodljivosti grane mreže između čvorišta i i čvorišta j:

The terms outside the main matrix diagonal are determined as negative value of the network branch conductivity between the node i and the node j:

$$
Y_{i,j} = -\frac{1}{Z_{i,j}} \Bigg|_{(i \neq j)} . \tag{17}
$$

Za izračun stanja u mreži primijenjen je Gaussov iteracijski postupak, u matematici poznat pod nazivom Jacobiev iteracijski postupak. Primjena Gaussovog postupka je nužna iz razloga što nisu poznati argumenti napona čvorišta u kojima su spojeni generatori. Za jednoznačno definiranje čvorišta u kojima su spojeni generatori (slika 2 čvorišta 8, 9, 10 i 11) potrebni su modul napona generatora U_{Gn} i djelatna snaga generatora P_{Gn} (indeks Gn je redni broj generatora) koji je spojen u promatrano čvorište. Napon i snaga pojedinog generatora dobivaju se izračunom, iz matematičkog modela sinkronog generatora. Kompleksna vrijednost napona čvorišta 7, na kojega je spojen nadomješteni ekvivalent elektroenergetskog sustava, iznosi $V_7 = j \cdot 0$.

For the calculation of the situation in the network, the Gauss iterative method, known in mathematics as the Jacobi iterative procedure, was applied. The application of the Gauss method is necessary because the operators of the voltage of the nodes in which the generators are connected are not known. For an unambiguous definition of hubs in which the generators are connected (Figure 2, 8, 9, 10 and 11), the generator voltage magnitude U_{Gn} and the active power of the generator P_{Gn}, which is connected to the observed node, are necessary (the index is the generator's ordinal number). The voltage and the power of the particular generator are obtained by calculation from the mathematical model of the synchronous generator. The complex value of node 7, to which the substitute equivalent of the electric power system is connected, amounts to $V_7 = j \cdot 0$.

U prvoj iteraciji iznosi argumenata napona generatora za čvorišta u kojima su generatori spojeni (8, 9, 10 i 11) se pretpostavljaju. Rješavanjem sustava jednadžbi (15) odrede se nepoznati iznosi potencijala ostalih čvorišta (1, 2, 3, 4, 5 i 6). Vrijednost argumenta napona generatora za svaku sljedeću iteraciju određuje se prema:

In the first iteration, the values of the generator voltage operators for the nodes in which the generators are connected (8, 9, 10 and 11) are assumed. By solving the equations system (15), unknown values of the potentials of the other hubs (1, 2, 3, 4, 5 and 6) are determined. The value of the operators of the generator voltage for each subsequent iteration is determined according to:

$$\begin{bmatrix} \varphi_8 \\ \varphi_9 \\ \varphi_{10} \\ \varphi_{11} \end{bmatrix} = \begin{bmatrix} \varphi_3 + \dfrac{P_{G4} x_{3-8}}{|U_{G4}||V_3|} \\ \varphi_4 + \dfrac{P_{G3} x_{4-9}}{|U_{G3}||V_4|} \\ \varphi_1 + \dfrac{P_{G2} x_{1-10}}{|U_{G2}||V_1|} \\ \varphi_1 + \dfrac{P_{G1} x_{1-11}}{|U_{G1}||V_1|} \end{bmatrix}, \quad (18)$$

gdje su:

$\varphi_8, \varphi_9, \varphi_{10}, \varphi_{11}$ – kutovi fazora napona čvorišta u kojem se nalazi generator, a

$\varphi_3, \varphi_4, \varphi_1$ – kutovi fazora susjednih čvorišta, slika 2.

Nakon što se odrede kutovi fazora čvorišta u kojima su spojeni generatori (18) određuju se nove kompleksne vrijednosti napona tih čvorišta. S novim kompleksnim vrijednostima napona čvorišta (8, 9, 10 i 11) rješava se sustav jednadžbi (15). Opisani postupak se ponavlja sve dok se razlika argumenata napona čvorišta (8, 9, 10 i 11), u koraku k i koraku $(k-1)$ ne smanji na zanemarivo mali iznos $(\varphi_i(k) - \varphi_i(k-1) < 10^{-4})$.

Odabrano vrijeme diskretizacije, odnosno vremenski korak nakon kojeg se rješava jednadžba (16) i vrijeme integracije za rješavanje modela sinkronih generatora je jednako i iznosilo je $T = 0{,}005$ s. Broj iteracija do postizanja zadane točnosti $(\varphi_i(k) - \varphi_i(k-1) < 10^{-4})$ za rješavanje jednadžbe (16) iznosio je maksimalno 10 za vrijeme trajanja poremećaja, a u stacionarnom stanju broj iteracija kretao se od 1 do 2. Numerička stabilnost postupka provjerena je povećavanjem koraka integracije pri čemu je zadržana konvergentnost u rješavanju sustava jednadžbi (15) kao i numerčka stabilnost u rješavanju diferencijalnih jednadžbi matematičkog modela sinkronih generatora i sustava uzbude.

whereat it is as follows:

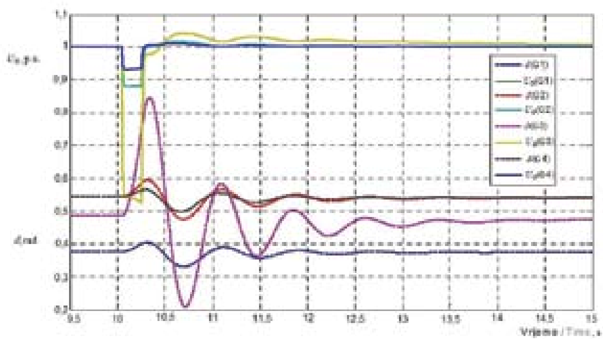
$\varphi_8, \varphi_9, \varphi_{10}, \varphi_{11}$ – voltage phasor angles of the node in which the generator is connected and

$\varphi_3, \varphi_4, \varphi_1$ – angles of the phasors of the neighbouring hubs, Figure 2.

After the determination of the phasor angles of the node in which the generators are connected (18), new complex values of the voltages of those are determined. With new complex values of the voltages of the (8, 9, 10 and 11), the equations system is solved (15). The described procedure is repeated until the difference of the operators of the voltages (8, 9, 10 and 11) in step k and step $(k-1)$ is reduced to a negligibly small value $(\varphi_i(k) - \varphi_i(k-1) < 10^{-4})$.

The selected discretization period, that is, the temporal step after which the equation (16) is solved and the period of integration for solving the synchronous generator models were equal and amounted to $T = 0{,}005$ s. The number of iterations until the achievement of the set accuracy for solving the equation (16) amounted to max. 10 for the duration of the disruption, and in steady state, the number of iterations fluctuated from 1 to 2. The numeric stability of the procedure was verified by increasing the integration steps whereat the convergent quality was kept in solving equations systems (15), as well as the numeric stability in solving differential equations of the mathematical model of the synchronous generator and the excitation system.

By applying the derived procedure, calculations



Slika 3 — Odziv napona generatora G3 i kutova opterećenja generatora G3 pri pojavi kratkog spoja u čvorištu 6 mreže na slici 2

Figure 3 — Response of the G3 generator voltage and the G3 generator load angles at the occurrence of a short circuit in hub 6 of the network from Figure 2

Primjenom razvijenog postupka proveden je simulacijski proračun odziva veličina modela sinkronih generatora pri nastanku kratkog spoja u prijenosnoj mreži. U mreži na slici 2 simulirana je pojava kratkog spoja u čvorištu 6. Kratki spoj simuliran je smanjivanjem stacionarnog iznosa impendancije $Z_{6\text{-}0} = \mathrm{j} \cdot 10^3$ na iznos $Z_{6\text{-}0} = \mathrm{j} \cdot 10^{-3}$ u trajanju od $0{,}2$ s. Rezultat simulacijskog proračuna pokazan je na slici 3. Vidljive su značajne razlike u iznosima poremećaja na generatorima zbog različite električke udaljenosti generatora od mjesta kvara. Na generatoru G3 maksimalno nadvišenje kuta opterećenja iznosilo je 180 % stacionarne vrijednosti dok je za generator G1 maksimalno nadvišenje kuta opterećenja iznosilo samo 105 % stacionarne vijednosti kuta opterećenja. Postignuta maksimalna nadvišenja kuta opterećenja odgovaraju maksimalnim propadima napona na sabirnicama generatora.

2.3 Matematički model sustava uzbude

Sustavi uzbude generatora modelirani su na temelju standardnih modela iz [6] koji se koriste za simulacijske proračune. Samozbudni sustav modeliran je prema standardnom modelu uzbudnog sustava označen kao ST1A. U ostvarenju sustava uzbude prema modelu ST1A uzbudnik je izveden kao punoupravljivi ispravljač u mosnom spoju, koji se napaja sa stezaljki sinkronog generatora preko transformatora. Struktura sustava uzbude koji je primijenjen za simulacijske proračune pokazana je na slici 4a. Standardni model ST1A je za potrebe ovog proračuna pojednostavljen tako što su isključeni stabilizacijski i kompenzacijski blokovi. Provedena pojednostavljenja nemaju znatnog utjecaja na rezultate proračuna ponašanja sinkronog generatora u uvjetima pojave kratkog spoja na mreži [4].

were undertaken of the response of the sizes of the synchronous generator models in short-circuit disturbance in the transmission network. In the network in Figure 2, the occurrence of a short circuit in node 6 was simulated. The short circuit was simulated by reducing the stationary impedance value of $Z_{6\text{-}0} = \mathrm{j} \cdot 10^3$ to the value $Z_{6\text{-}0} = \mathrm{j} \cdot 10^{-3}$ in the duration of $0{,}2$ s. Calculations result is shown in Figure 3. Significant differences are visible in the extents of the disruptions on the generators depending on the generator's varying electric distance from the place of the failure. On the G3 generator, maximum altitudes of the load angle amounted to 180 % of the stationary value, while on the G1 generator, the maximum altitudes of the load angle amounted only to 105 % of the load angle stationary value. The achieved maximum altitudes of the load angle match the maximum voltage drops on the generator's busbars.

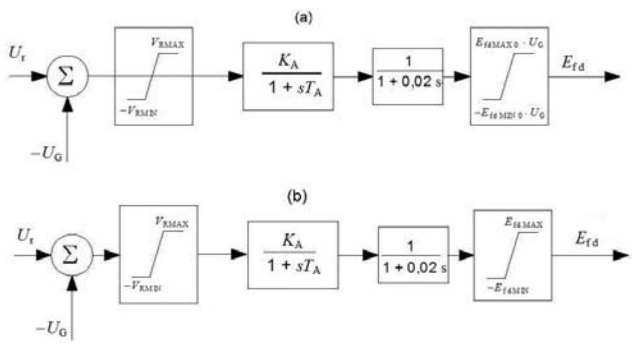
2.3 Mathematical model of the excitation system

Generator excitation systems are modelled based on standard models from [6] which are used for calculations. The self-excitation system is modelled according to the standard model of the excitation system marked as ST1A. In the execution of the excitation system according to the ST1A model, the exciter is designed as a fully controlled rectifier in a bridge connection which is supplied from the terminals of the synchronous generator through the transformer. The structure of the excitation system which was applied for calculations is shown in Figure 4a. The standard ST1A model was simplified for the needs of this calculation so as to include the stabilization and compensation blocks. The undertaken simplifications have no significant impact on the results of the calculation of the behaviour of the synchronous generator in the circumstances of occurrence of a short circuit in the network [4].
The properties of the excitation system of the ST1A

Značajke sustava uzbude tipa ST1A su pojačanje regulatora $K_A > 100$ i vremenska konstanta $T_A = 0{,}02$ s. Zbog činjenice da se uzbudnik napaja preko transformatora koji je spojen na izvode generatora ovaj sustav se izvodi s odgovarajućim forsiranjem. Utjecaj napona generatora U_G na iznos napona uzbude E_{fd} ogleda se u promjenljivom iznosu ograničenja za maksimalno mogući iznos napona uzbude. Maksimalni pozitivni odnosno negativni iznos ograničenja napona uzbude su: $E_{fdMAX} = E_{fdMAX0} \cdot U_G$, $E_{fdMIN} = -E_{fdMAX0} \cdot U_G$, gdje je E_{fdMAX0} maksimalni mogući napon uzbude određen faktorom forsiranja.

type are the gain of the regulator $K_A > 100$ and the time constant $T_A = 0{,}02$ s. Because of the fact that the exciter is supplied through the transformer which is connected to the leads of the generator, this system is designed with adequate forcing. The impact of the generator voltage U_G on the amount of the excitation voltage E_{fd} is reflected in the variable amount of limitation for the maximum possible amount of the excitation voltage. The maximum positive, that is, negative amounts of the excitation limitation are: $E_{fdMAX} = E_{fdMAX0} \cdot U_G$, $E_{fdMIN} = -E_{fdMAX0} \cdot U_G$, where E_{fdMAX0} is the maximum possible excitation voltage defined by the forcing factor.

The separate excitation system is modelled accord-



Slika 4 — Blokovski prikaz sustava uzbude
Figure 4 — Block overview of the excitation systems

Sustav s nezavisnom uzbudom modeliran je prema preporuci [6] kao AC4A, a pokazan je na slici 4b . Uzbuda glavnog sinkronog generatora napaja se preko ispravljača sa stezaljki pomoćnog sinkronog generatora koji je ugrađen na zajedničkoj osovini s glavnim generatorom.

U ovom modelu pretpostavlja se da je napon izvora za napajanje uzbude glavnog sinkronog generatora konstantan, zanemaren je pad napona u stanju vođenja tiristora, što znači da se regulacija napona odvija u linearnom području sve dok napon uzbude ne dostigne maksimalni pozitivni odnosno negativni iznos.

S ciljem da se omogući usporedba rezultata dobivenih izračunom osnovni parametri regulatora postavljeni su na jednake iznose u samouzbudnom sustavu i sustav s nezavisno uzbudom i to: pojačanje regulatora podešeno je na $K_A = 100$, a vrijeme kašnjenje regulatora na $T_A = 0{,}02$ s .

ing to the recommendation [6] as AC4A and shown in Figure 4b. The excitation of the main synchronous generator is supplied through the rectifier from the terminals of the auxiliary synchronous generator which is installed on the same shaft with the main generator.

In this model, it is assumed that the voltage of the source for supplying the excitation of the main synchronous generator is constant; the voltage drop in the thyristor conduction state is neglected, and this means that voltage regulation is in a linear area all until the excitation voltage reaches either the positive, or the negative amount.

With the aim to enable the comparison of results obtained by calculation, the basic parameters of the regulator are set at equal amounts in the self-excitation system and in the separate excitation system and that being: regulator's gain is set at $K_A = 100$ and its time constant is set at $T_A = 0{,}02$ s .

3 CALCULATION RESULTS

3 REZULTATI PRORAČUNA

Rezultati proračuna kuta opterećenja generatora pri pojavi kratkog spoja na mreži u čvorištu 6 pokazani su na slikama 5 i 6 dok su na slikama 7 i 8 pokazani rezultati dobiveni pri pojavi kratkog spoja na mreži u čvorištu 5. U oba slučaja proračun je napravljen za sustav s nezavisnom uzbudom i samouzbudni sustav u potpuno jednakim pogonskim uvjetima. Djelatne snage sinkronih generatora (izražene u pu generatora G3) koji su uključeni u modelirani elektroenergetski sustav su redom:

$P_{G1} = 0{,}6\ \mathrm{p \cdot u}$; $P_{G2} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G3} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G4} = 0{,}9\ \mathrm{p \cdot u}$

Prva grupa proračuna provedena je u uvjetima pojave kratkog spoja u čvorištu 6 pri čemu je kratki spoj simuliran smanjivanjem reaktancije koja spaja čvorište 6 s referentnim čvorištem 0 (slika 2) na vrijednost od $Z_{6-0} = \mathrm{j} \cdot 10^{-3}$. Uspoređeni su odzivi kuta opterećenja δ generatora G3, za različita vremena trajanja kratkog spoja (slike 5 i 6).

Najprije je odabrano vrijeme trajanja kratkog spoja $T_k = 100$ ms, što odgovara tipičnom vremenu prorade zaštite voda u prvoj zoni, zatim je vrijeme trajanja kratkog spoja povećano je na $T_k = 200$ ms i nakon toga proračun je proveden za vrijeme trajanja kratkog spoja $T_k = 400$ ms što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti.

Rezultati izračuna pokazani su na slici 5a dok su na slici 5b dane razlike kuta opterećenja $\Delta\delta$ generatora G3 s nezavisnom uzbudom i samouzbudom za odabrana vremena trajanja kratkog spoja.

Results of the calculation of the generator load angle in short-circuit disturbance on the network in node 6 are shown in Figures 5 and 6, while Figures 7 and 9 show the results obtained in short-circuit disturbance on the network in node 5. In both cases, the calculation was performed for the system with separate excitation and the self-excitation system in in same conditions. Active powers of synchronous generators (stated in G3 generator pu) which are included in the modelled electric power system are consecutively as follows:

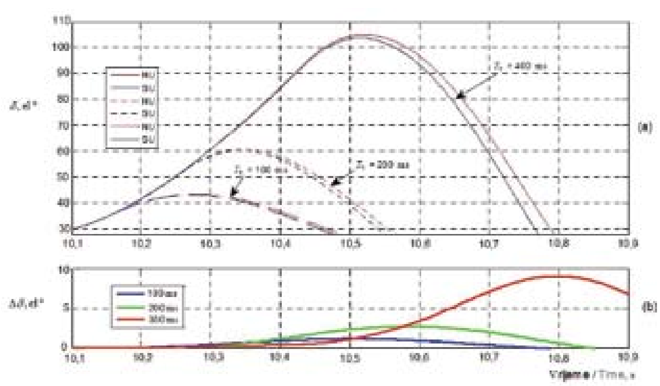
$P_{G1} = 0{,}6\ \mathrm{p \cdot u}$; $P_{G2} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G3} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G4} = 0{,}9\ \mathrm{p \cdot u}$

The first calculation group was designed in the conditions of occurrence of a short circuit in node 6 whereat the short circuit was simulated by reducing the reactance which connects node 6 to the reference node 0 (Figure 2) to the amount of $Z_{6-0} = \mathrm{j} \cdot 10^{-3}$. Responses of the load angle δ of the G3 generator were compared for different durations of the short circuit (Figures 5 and 6).

At first, the duration of the short circuit $T_k = 100$ ms was chosen which matches the typical time of the tripping of the line in the first zone, then the duration of the short circuit was increased to $T_k = 200$ ms and after that, the calculation was performed for the duration of the short circuit $T_k = 400$ ms which matches the critical time of duration of the short circuit according to the transitive stability criterion.

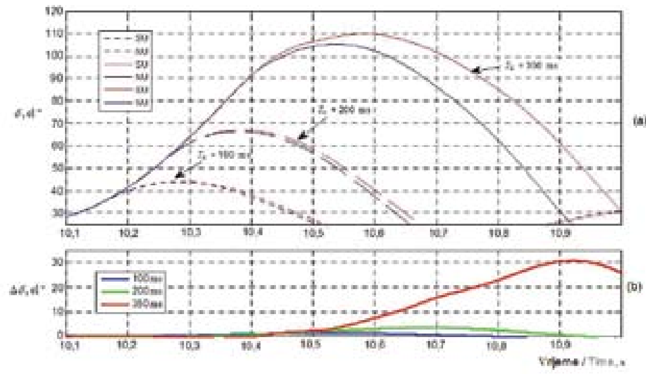
Calculation results were shown in Figure 5a, while in Figure 5b the differences of the load angle $\Delta\delta$ of the G3 generator with separate excitation and self-excitation are given for the chosen durations of the short circuit.

With the aim to determine the behaviour of differ-



Slika 5 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim(NU) i samouzbudnim (SU) sustavom uzbude za slučaj kratkog spoja u čvorištu 6 pri trajanju kratkog spoja u mreži od $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 400$ ms

Figure 5 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation (SE) systems for the case of the short circuit in hub 6 for the duration of the short circuit in the network of $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 400$ ms



Slika 6 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim(NU) i samouzbudnim (SU) za slučaj kratkog spoja u čvorištu 6 uz isključeni vod 400 kV između čvorišta 1 i 7 pri trajanju kratkog spoja u mreži od T_k = 100 ms, T_k = 200 ms i T_k = 350 ms

Figure 6 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation (SE) systems for the case of the short circuit in hub 6 with a switched-off 400 kV-line between hubs 1 and 7 for the duration of the short circuit in the network of T_k = 100 ms, T_k = 200 ms and T_k = 350 ms

S ciljem da se odredi ponašanje različitih sustava uzbude u promijenjenim prilikama u prijenosnoj mreži isključen je vod 400 kV između čvorišta 1 i 7 i ponovljen je pokus kratkog spoja u čvorištu 6 (slika 5). Isključenje 400kV voda simulirano je povećanjem reaktancija Z_{1-6} (slika 2) na iznos od Z_{1-6} = j ·1 000.

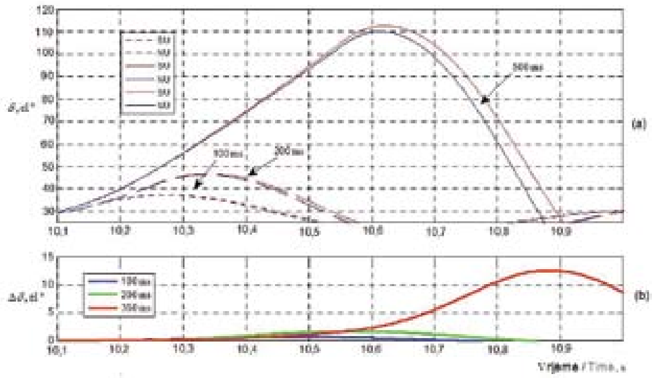
Proračun je napravljen za trajanje kratkog spoja od T_k = 100 ms, zatim je ponovljen za trajanje kratkog spoja od T_k = 200 ms i za trajanje kratkog spoja od T_k = 350 ms što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti. Razlike kutova opterećenja za sustav s nezavisnom uzbudom i samouzbudni sustav $\Delta\delta$ za generator G3 dane su na slici 6b.

Druga grupa proračuna provedena je u uvjetima pojave kratkog spoja u čvorištu 5 pri čemu je kratki spoj simuliran smanjivanjem reaktancije koja spaja čvorište 5 s referentnim čvorištem 0 (slika 2) s iznosa od $Z_{5-0} = j \cdot 10^3$ na $Z_{5-0} = j \cdot 10^{-3}$. Na slici 7a dani su usporedni odzivi kuta opterećenja sustava s nezavisnom uzbudom i samouzbudnog sustava, gdje su odabrana trajanja kratkog spoja u čvorištu 5 iznosila T_k = 100 ms, T_k = 200 ms i T_k = 500 ms, što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti. Na slici 7b pokazana je razlika izračunatih kutova opterećenja $\Delta\delta$ za generator G3 kada je primijenjen sustav samouzbude i sustava s nezavisnom uzbudom.

ent excitation systems in different circumstances in the transmission network, the 400 kV line was switched off between nodes 1 and 7, and the test of the short circuit in node 6 was repeated (Figure 5). The switching-off of the 400 kV line was simulated by increasing the reactance Z_{1-6} (Figure 2) to the amount of Z_{1-6} = j ·1 000.

The calculation was performed for the duration of the short circuit of T_k = 100 ms and then repeated for the duration of the short circuit of T_k = 200 ms, and for the duration of the short circuit of T_k = 350 ms which matches the critical time of duration of the short circuit according to the transitive stability criterion. Differences of load angles for the system with separate excitation and self-excitation system $\Delta\delta$ for the G3 generator are given in Figure 6b.

The second calculation group was performed in the conditions of occurrence of a short circuit in node 5 whereat the short circuit was simulated by reducing the reactance which connects node 5 to the reference node 0 (Figure 2) from the amount of $Z_{5-0} = j \cdot 10^3$ to $Z_{5-0} = j \cdot 10^{-3}$. Figure 7a provides the parallel responses of the load angles of the system with separate excitation and of the self-excitation system where the selected durations of the short circuit in node 5 amounted to T_k = 100 ms, T_k = 200 ms and T_k = 500 ms which matches the critical time of duration of the short circuit according to the transitive stability criterion. Figure 7b shows the difference of calculated load angles $\Delta\delta$ for the G3 generator when the self-excitation system and the separate excitation systems are applied.



Slika 7 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim (NU) i samouzbudnim (SU) sustavom uzbude za slučaj kratkog spoja u čvorištu 5 pri trajanju kratkog spoja u mreži od $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 500$ ms

Figure 7 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation (SE) systems for the case of the short circuit in hub 5 for the duration of the short circuit in the network of $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 500$ ms

U nastavku je učinjen izračun za slučaj pojave kratkog spoja u čvorištu 5 u uvjetima koji nastaju pri trajnom ispadu mreže 400 kV i radu agregata na mreži 220 kV. Da bi se modeliralo opisano stanje potrebno je promijeniti vrijednosti reaktancija koje gledaju u čvoriše 6 tako da su, za slučaj trajnog ispada mreže 400 kV, reaktancije prema krutoj mreži povećane na vrijednosti: $Z_{1-7} = j \cdot 0{,}5$, $Z_{2-7} = j \cdot 0{,}5$i $Z_{3-7} = j \cdot 0{,}5$.

Proračun je učinjen za različita vremena trajanja kratkog spoja u čvorištu 5: $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 300$ ms što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti, a dobiveni rezultati pokazani su na slici 8.

Postignute razlike kuta opterećenja $\Delta\delta$ generatora G3 za slučaj samouzbudnog sustava sustava s nezavisnom uzbudom i pokazane su na slici 8b.

4 ZAKLJUČAK

Razvijen je matematički model elektroenergetskog sustava s više sinkronih generatora u kojemu su generatori opisani nelinearnim matematičkim modelom. Istražen je utjecaj načina napajanja sustava uzbude na kutnu stabilnost generatora u uvjetima pojave kratkog spoja u mreži. S razvijenim postupkom provedeni su proračuni kuta opterećenja generatora u uvjetima pojave kratkog spoja na prijenosnoj mreži. Izračun je učinjen za različite konfiguracije prijenosne mreže i za različita vremena trajanja kratkog spoja. Rezultati simulacijskih proračuna pokazani su usporedbom kutova optereće-

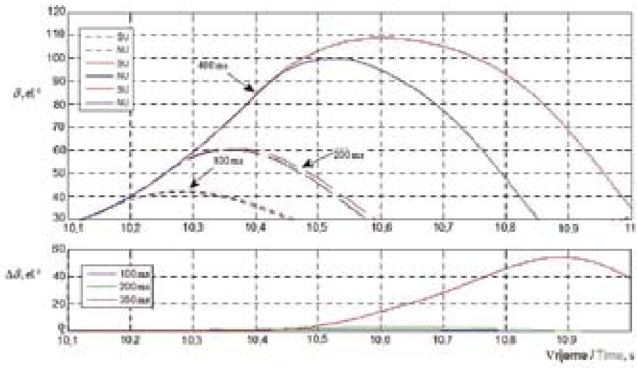
In the text below, calculation was made for the case of occurrence of a short circuit in node 5 in the conditions which appear at permanent outage of the 400 kV network and operation of the power generating set on the 220 kV network. In order to model the stated condition, it is necessary to change the values of the reactance which look at node 6 so that, in case of permanent outage of the 400 kV network, the reactance towards the infinite network are increased to the values: $Z_{1-7} = j \cdot 0{,}5$, $Z_{2-7} = j \cdot 0{,}5$ and $Z_{3-7} = j \cdot 0{,}5$.

The calculation was performed for different durations of the short circuit in node 5: $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 300$ ms which matches the critical time of duration of the short circuit according to the transitive stability criterion. The obtained results are shown in Figure 8.

The achieved differences of the load angles $\Delta\delta$ of the G3 generator for the case of the self-excitation system and the separate excitation system are shown in Figure 8b.

4 CONCLUSION

The paper elaborates on the mathematical model of the electric power system with several synchronous generators in which the generators are modelled by a non-linear mathematical model. The impact of the manner of supplying the excitation system on the angular stability of the generator was researched in the circumstances of occurrence of a short circuit in the network. By virtue of the derived procedure, load angle calculations were performed in the conditions of occurrence of a short circuit on the transmission network. The calculation was performed for different



Slika 8 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim (NU) i samouzbudom (SU) sustavom uzbude za slučaj kratkog spoja u čvorištu 5 pri trajnom ispada mreže 440 kV i radu agregata na mreži 220 kV pri trajanju kratkog spoja u mreži od T_k = 100 ms, T_k = 200 ms i T_k = 300 ms

Figure 8 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation systems for the case of the short circuit in hub 5 at permanent outage of the 440 kV-network and operation of the power generating set on the 220 kV-network for the duration of the short circuit in the network of T_k = 100 ms, T_k = 200 ms and T_k = 300 ms.

nja generatora koji se postižu sa samouzbudnim sustavom i sustavom s nezavisnom uzbudom. Proračuni su provedeni za slučaj agregata u HE Dubrovniku.

Rezultati dobiveni proračunom pokazuju da agregati s nezavisnom uzbudom imaju bolje dinamičke karakteristike po kriteriju kutne stabilnosti jer pri identičnom poremećaju postižu manje kutove opterećenja iz čega se zaključuje da su otporniji na poremećaje u mreži. Razlike između kutova opterećenja kod promatranih sustava uzbude povećavaju se s povećanjem vremena trajanja kratkog spoja na mreži. Kao što se i očekivalo, proračuni su pokazali da dominantni utjecaj na pogonsku stabilnost generatora ima mjesto kvara u prijenosnoj mreži.

Postavljenim modelom moguće je istražiti utjecaj generatora s nezavisnom uzbudom na ukupnu kutnu stabilnost elektroenergetskog sustava. U razmatranje se može uzeti bitno veći dio elektroenergetskog sustava i provesti proračune za nekoliko karakterističnih pogonskih stanja sustava i pritom odrediti utjecaj koji bi odabrani generatori s nezavisnim sustavom uzbude imali na kutnu stabilnost elektroenergetskog sustava.

Razvijeni postupak omogućuje relativno jednostavno proširenje na način da se poveća broj čvorišta, grana mreže i generatora.

transmission network configurations and for different durations of the short circuit. The results of calculations are shown by comparing the generator load angles which are achieved by the self-excitation system and the separate excitation system. The calculations were performed for the case of the power generating set at the Dubrovnik hydroelectric power plant.

The results obtained by calculation show that the independent-excitation power generating sets have better dynamic characteristics according to the angular stability criterion because at an identical disruption they achieve smaller load angles. This gives rise to the conclusion that these are more resistant to the disruptions in the network. The differences between the load angles at the observed excitation systems increase with the increase of the time of duration of the short circuit in the network. As expected, the calculations showed that the major impact factor on the generator's drive stability is the place of the failure in the transmission network.

The set model provides for the research of the impact of the self-excitation generator on the total angular stability of the electric power system. The major part of the electric power system can be included in the observation and calculations can be performed for several characteristic drive conditions of the system, and thereat the impact can be defined which the selected independent-excitation system generators would have on the angular stability of the electric power system.

The derived procedure provides for a relatively simple expansion so as to increase the number of hubs, network branches and generators.

LITERATURA / REFERENCES

[1] MEHMEDOVIĆ, M., Identifikacija parametara sustava regulacije uzbude sinkronih strojeva, Doktorska disertacija, Sveučilište u Zagrebu, Fakultet elektrotehnike i računarstva, Zagreb, 1995.

[2] KRAUSE, P.C., Analysis of Electrical Machinery and Drive Systems, Wiley US, 1996

[3] SIROTIĆ, Z., MALJKOVIĆ, Z., Sinkroni strojevi, CIP Zagreb, 1996.

[4] ANDERSON, P. M., FOUAD, A. A., Power System Control ans Stability Analysis, IEEE Standard 110, 1991

[5] OŽEGOVIĆ, M.; OŽEGOVIĆ, K., Električne energetske mreže, Svezak IV, Sveučilište u Splitu, Fakultet elektrotehnike, strojarstva i brodogradnje, Split, 1999.

[6] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE St. 421.5-2002 (Section 9)

[7] STOJSAVLJEVIĆ, M., MEHMEDOVIĆ, M., NEMEC, D., RADIĆ, Š., Analysis of Croatian Power System Dynamic Response In Case Of Switching The 400 kV Line Tumbri – Heviz In Real System // Med Power 2002, Proceedings (Abstracts), 3rd Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion / Hatziargyriou, N ; Braunstein, A ; Theopanus, A (ur.).

[8] MIŠKOVIĆ, M., MIROŠEVIĆ, M., Application of Data Monitoring of the Synchronous Generator Model // Proceedings Vol. 5 of 7, 11th International Power Electronics And Motion Control Conference, Riga Technical University, Latvia, 2004, 5-126 to 5-128

Adresa autora:

Dr. sc. **Mato Mišković**
mato.miskovic@hep.hr
HEP Proizvodnja, HE Dubrovnik
A.Starčevića 7
20000 Dubrovnik
Hrvatska
Doc. dr. sc. **Marija Mirošević**
marija.mirosevic@unidu.hr
Prof. dr. sc. **Mateo Milković**
Sveučilište u Dubrovniku
Branitelja Dubrovnika 29
2000 Dubrovnik
Hrvatska

Author's Adresses:

Mato Mišković, PhD
mato.miskovic@hep.hr
HEP Proizvodnja, HE Dubrovnik
A.Starčevića 7
20000 Dubrovnik
Croatia
Assistant prof. **Marija Mirošević**, PhD
marija.mirosevic@unidu.hr
Prof. **Mateo Milković**, PhD
University in Dubrovnik
Branitelja Dubrovnika 29
2000 Dubrovnik
Croatia

Uredništvo primilo rukopis:
2009-06-19

Prihvaćeno:
2009-08-20

Manuscript received on:
2009-06-19

Accepted on:
2009-08-20

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 neskraćenom 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/teze
   [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. Slavicu 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 PRIMJERCI

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.

INSTRUCTIONS TO AUTHORS

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 Artlicles 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 Conference
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 accordancs 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.