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

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

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

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

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

1 UVOD

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

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

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

1 INTRODUCTION

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

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

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

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

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

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

2 METODA ELEKTRIČNIH UDALJENOSTI

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

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

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

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

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

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

2 ELECTRICAL DISTANCE METHOD

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

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

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

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

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

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

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

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

$$D_{ij} = -\lg\left(\alpha_{ij}\right) \cdot \qquad (3)$$

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

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

$$D_{ij} = -\lg\left(\alpha_{ij}\right) \cdot \qquad (3)$$

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

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

3 MODEL TRŽIŠTA JALOVOM SNAGOM

3.1 Metodologija vrednovanja pomoćne usluge regulacije napona i jalove snage

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

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

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

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

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

3 REACTIVE POWER MARKET MODEL

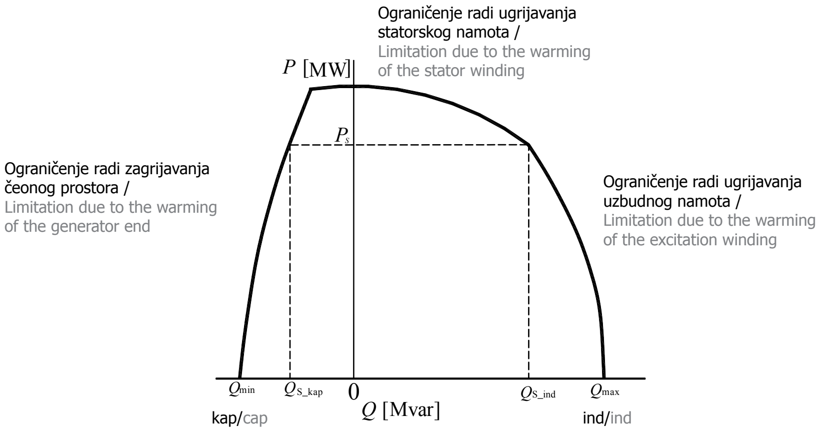
3.1 Methodology of evaluating the voltage and reactive power control support service

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

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

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

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



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

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

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

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

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

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

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

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

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

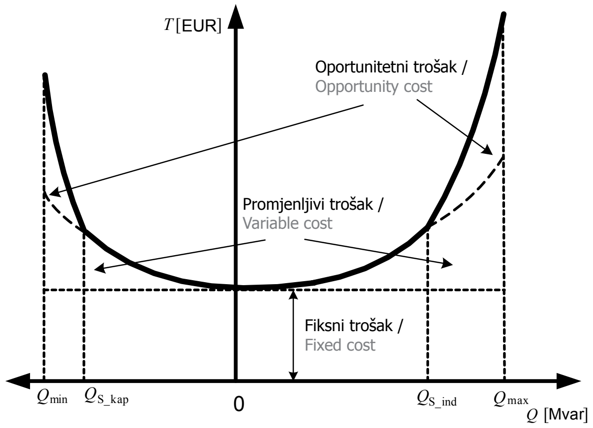
- Promjenjivi dio predstavlja troškove izazvane pretežno gubicima djelatne snage u uzbudnom i armaturnom namotu sinkronog generatora te u namotima blok transformatora. Ovisnost gubitaka u namotima o struji, odnosno izlazu jalove snage, je kvadratna (I^2R) te se tako ovisnost troškova i proizvedene jalove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

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

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

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

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



Slika 2 — Krivulja troškova proizvodnje jalove snage sinkronog generatora

Figure 2 — Cost curve of reactive power production by the synchronous generator

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

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

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

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

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

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

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

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

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

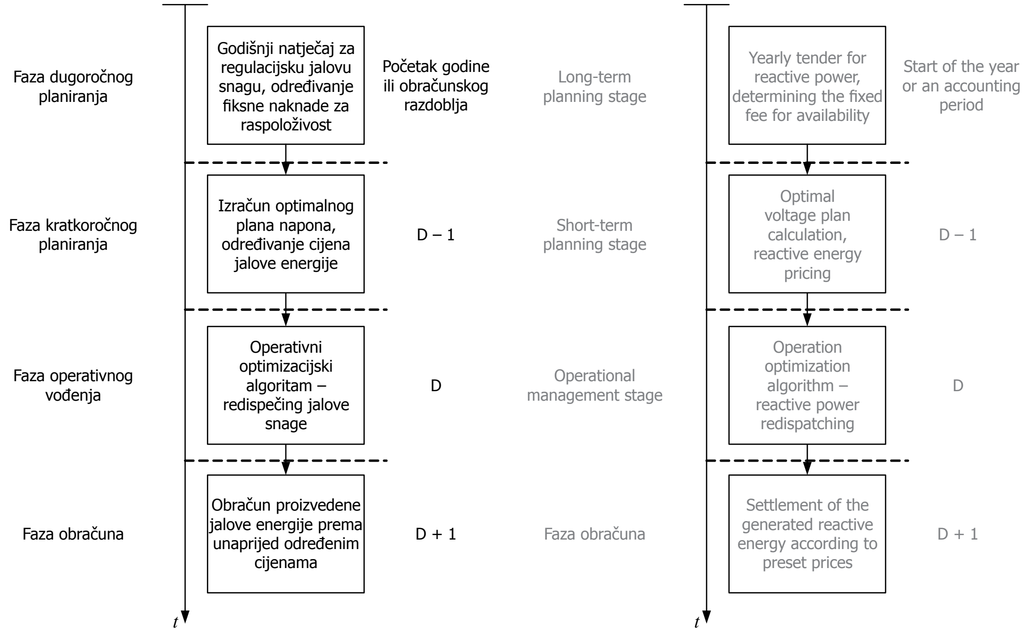
Based on a technical and economic analysis, which includes a study of the amount of fixed costs as well as the electrical position and contribution to the maintenance of voltage in the network, a list of synchronous generators is compiled which during the year will provide the voltage control ancillary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

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

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

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

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



Slika 3 — Model procesa nabave jalove snage i energije

Figure 3 — Model of reactive power and energy procurement process

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

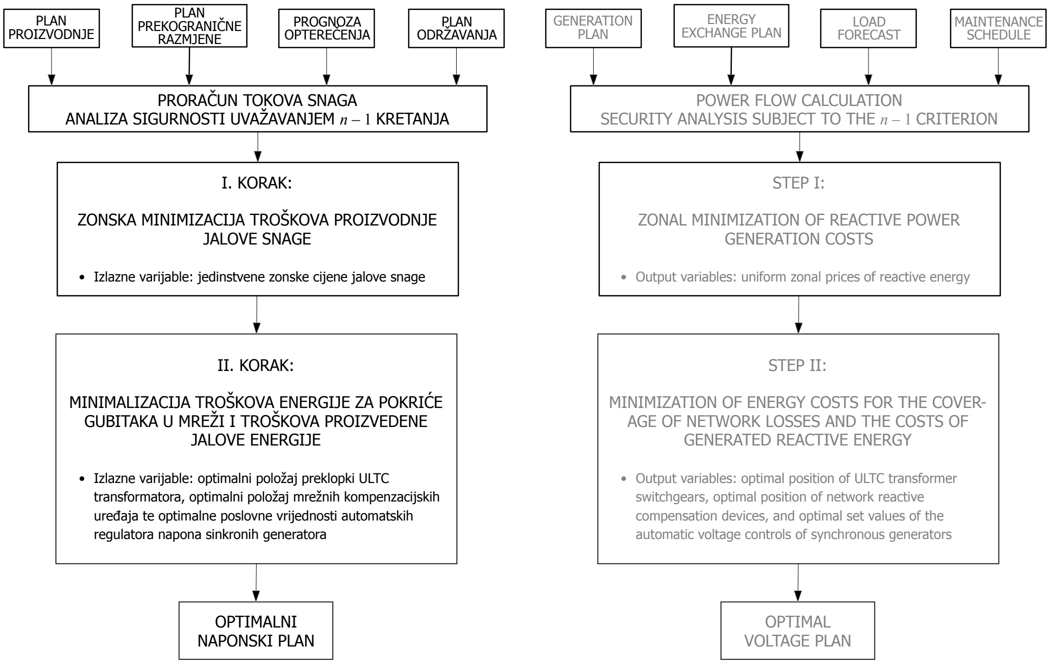
the uniform zonal prices of reactive energy and, second, to define the voltage plan based on minimized total costs of the TSO. The algorithm consists of two steps, where the zonal prices of reactive energy as the output of the first optimization step are at once the required input for the second optimization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

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

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

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

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



Slika 4 — Dvo-razinski optimizacijski algoritam u fazi kratkoročnog planiranja
Figure 4 — Two-level optimization algorithm in the short-term planning stage

Problem zonskog minimiziranja troškova proizvodnje jalove snage ima sljedeći oblik:

Minimiziranje zonske funkcije cilja oblika:

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

Minimization of the zonal goal function of the following form:

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

gdje je:

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

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

where:

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

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

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

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

i ograničenja tipa nejednakosti:

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

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

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

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

gdje je:

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

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

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

and the limitations of inequality type:

where:

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

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

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

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

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

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

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

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

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

gdje je:

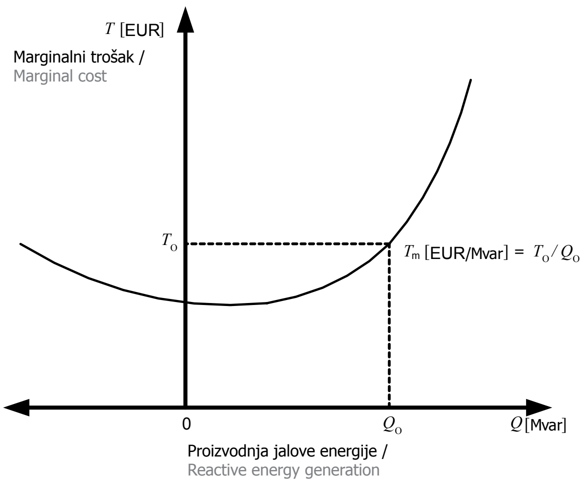
a, b – koeficijenti pravca koji aproksimira krivulju pogonskog dijagama generatora,
$P_{\mathrm{G}i\mathrm{S}}$ – zadana proizvodnja djelatne snage u čvorištu i (slika 1),
$Q_{\mathrm{G}i\mathrm{S}}$ – maksimalna proizvodnja jalove snage u čvorištu i s obzirom na zadanu proizvodnju djelatne snage u čvorištu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

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

where:

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

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



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

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

— minimiziranje gubitaka u mreži ima za posljedicu više vrijednosti napona u čvorištima mreže te maksimiziranje prijenosne moći, no i veće troškove proizvodnje jalove snage te smanjenje pričuve jalove snage u sinkronim generatorima. Dodatno, moguć je učestali angažman vrlo skupe elektrane bliske centru potrošnje,

— minimiziranje proizvodnje jalove snage posredno donosi sljedeće pozitivne i negativne učinke: niže vrijednosti napona u čvorištima mreže i veće gubitke u mreži, no i veću pričuvu jalove snage u sinkronim generatorima. Pri tome postoji opasnost od angažiranja jeftinih, ali udaljenih elektrana što dodatno narušava uvjete u mreži. No, za očekivati je da se zonskim pristupom donekle izbjegavaju spomenute negativne posljedice budući da je izbor generatora ograničen na usko područje – naponsku zonu.

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

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

— the minimization of network losses results in higher voltage values in network nodes and in the maximization of transmission capability, as well as higher costs of reactive power generation and a reduced reactive power reserve in the synchronous generators. What is also possible is a repeated engagement of a very expensive power plant near the consumption center,

— the minimization of reactive power generation indirectly has the following positive and negative effects: lower voltage values in network nodes and higher network losses, but also a higher reactive power reserve in the synchronous generators. This harbors a risk of engaging cheap but remote power plants, which additionally disrupts the network conditions. It is to be expected, however, that with the zonal approach the mentioned negative effects will be avoided, because the choice of generators is confined to a narrow area – the voltage zone.

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

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

gdje su:

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

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

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

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

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

where:

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

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

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

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

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

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

gdje je:

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

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

where:

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

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

$$T = T_{\mathrm{GUB}} + T_{\mathrm{Q}} \ , \qquad (15)$$

gdje je:

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

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

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

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

where:

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

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

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

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

4 REZULTATI TESTIRANJA NA MODELU HRVATSKOG EES-a

4.1 Podjela hrvatskog EES-a u naponske zone

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

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

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

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

4 RESULTS OF TESTING ON THE MODEL OF THE CROATIAN EPS

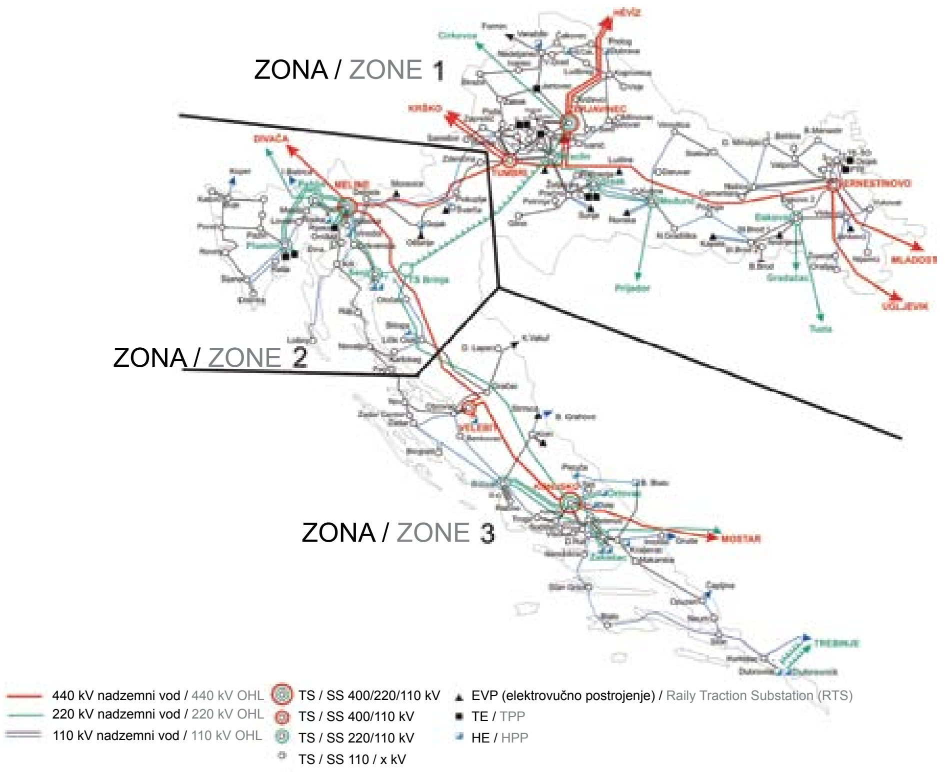
4.1 Division of the Croatian EPS into voltage zones

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

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

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

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



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

U tablici 1 predočena je pripadnost generatorskih čvorišta naponskim zonama.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.3 Rezultati ispitivanja optimizacijskog algoritma na modelu hrvatskog EES-a

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

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

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

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

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

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

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

Tablica 2 –Proizvodnja djelatne snage, regulacijski opseg i koeficijenti krivulje troškova proizvodnje jalove snage sinkronih generatora i kompenzacijskih uređaja hrvatskog EES-a
Table 2 – Active power generation, control range and coefficients of the cost curves of reactive power generation by the synchronous generators and reactive compensation devices of the Croatian EPS

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

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

Predloženi optimizacijski algoritam praktično je izveden korištenjem programskog okruženja

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

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

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

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

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

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

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

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

** Ponuda nije prihvaćena / Bid not accepted

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

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

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

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

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

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

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

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

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

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

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

** Ponuda nije prihvaćena / Bid not accepted

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

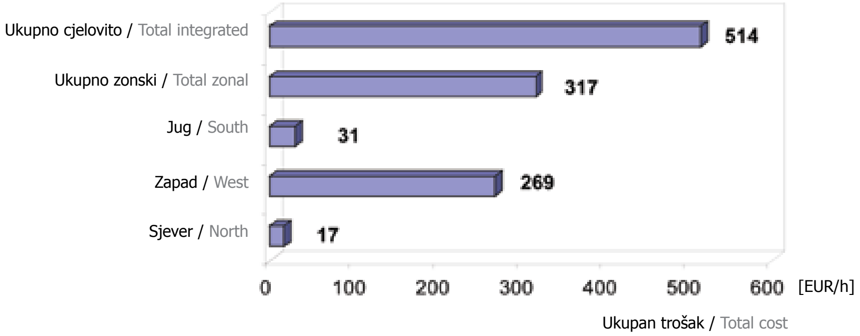
* Jedinstvena zonska cijena jalove energije / Uniform zonal price of reactive energy
** Ponuda nije prihvaćena / Bid not accepted

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

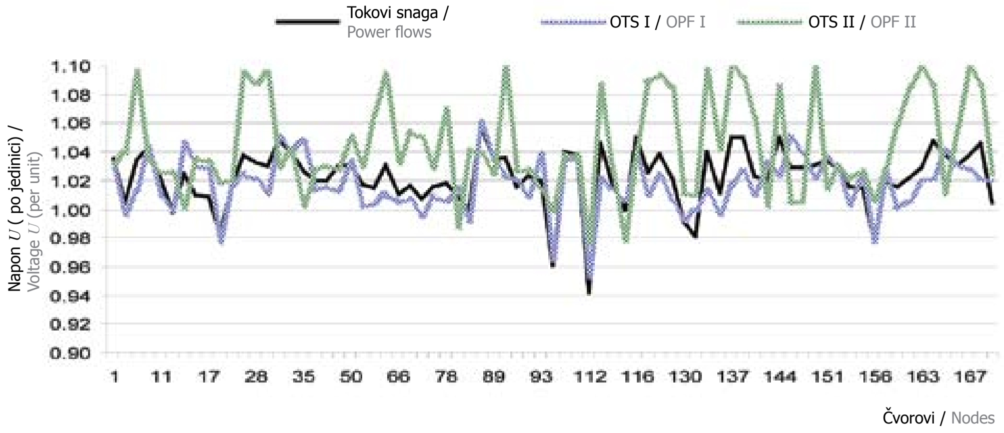
Slike 8, 9 i 10 prikazuju usporedbu naponskog profila za različite faze proračuna, za tri naponske zone. Slike 11, 12 i 13 prikazuju usporedbu proizvodnje jalove snage angažiranih izvora za različite faze proračuna, za tri naponske zone. Početno stanje predstavlja rezultate tokova snaga, OTS I odnosi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

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

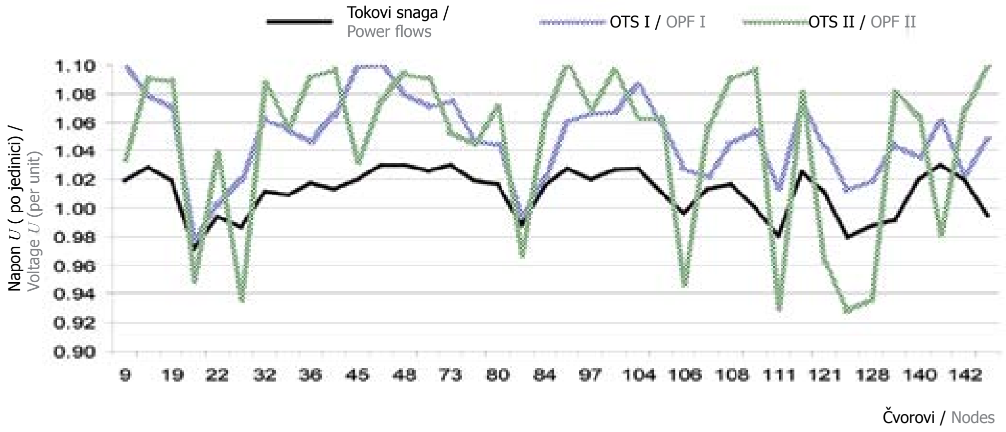
Figures 8, 9 and 10 give a comparison of the voltage profile for different calculation stages, for three voltage zones. Figures 11, 12 and 13 give a comparison of reactive power generation by engaged sources for different calculation stages, for three voltage zones. The initial state represents the power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

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

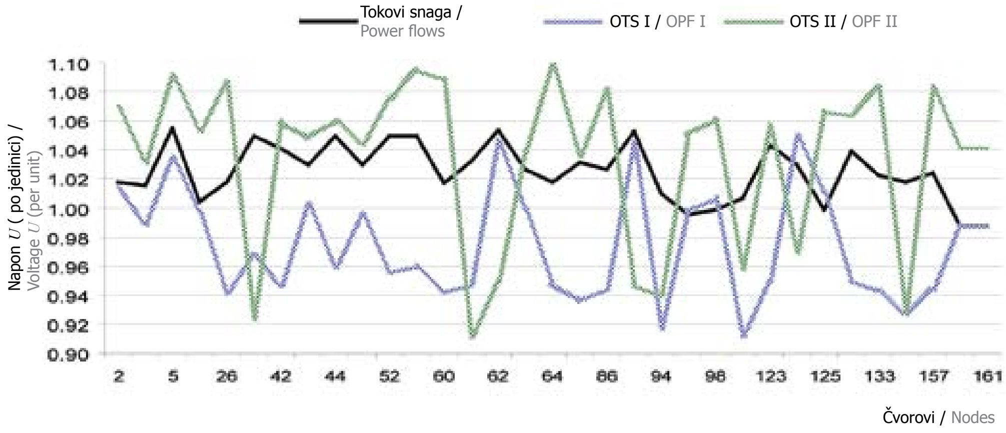
ULTC Transformator / ULTC Transformer	U_{n1} / U_{n2} (p.u.)			
	Početno stanje / Initial state	C_{GUB} [EUR/MWh]		
		10	50	90
Bilice 220/110 kV	1,00	1,00	0,91	0,90
Bilice 220/110 kV	1,00	1,00	0,95	0,97
Đakovo 220/110 kV	1,00	0,90	0,95	0,90
Ernestinovo 400/110 kV	1,00	1,02	0,99	1,03
Ernestinovo 400/110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



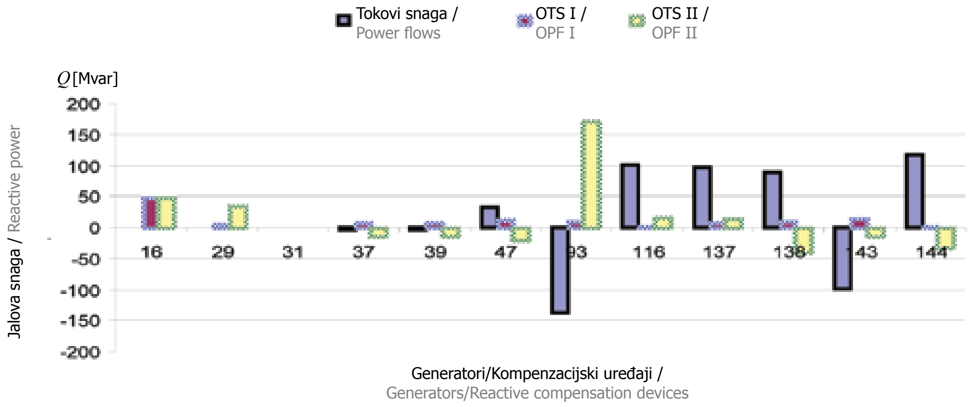
Slika 8 — Usporedba naponskog profila u zoni Sjever za različite faze proračuna
Figure 8 — Voltage profile comparison in zone North for different calculation stages



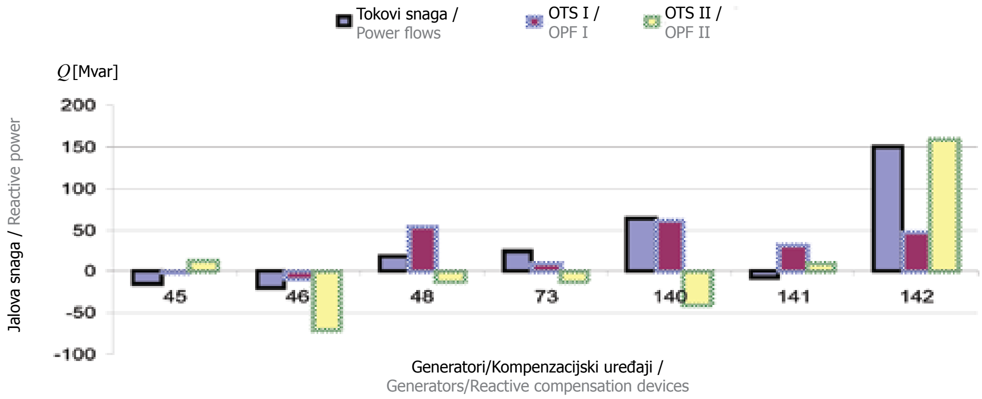
Slika 9 — Usporedba naponskog profila u zoni Zapad za različite faze proračuna
Figure 9 — Voltage profile comparison in zone West for different calculation stages



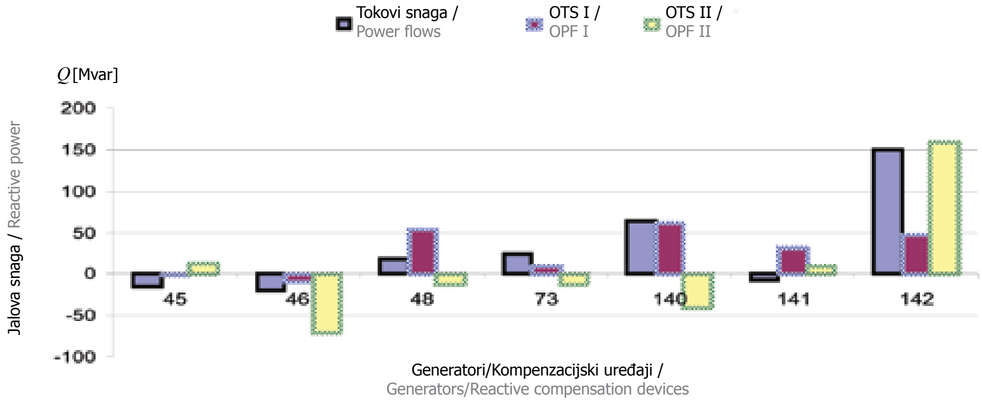
Slika 10 — Usporedba naponskog profila u zoni Jug za različite faze proračuna
Figure 10 — Voltage profile comparison in zone South for different calculation stages



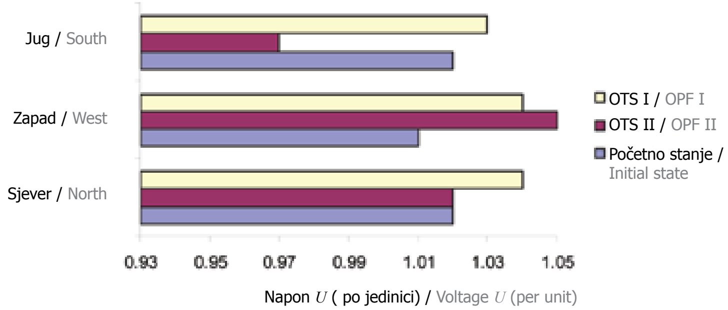
Slika 11 — Usporedba proizvodnje jalove snage angažiranih izvora u zoni Sjever za različite faze proračuna
Figure 11 — Comparison of reactive power generation by engaged sources in zone North for different calculation stages



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



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



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

5 ZAKLJUČAK

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

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

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

5 CONCLUSION

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

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

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

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

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

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

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