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DINAMIČKA ANALIZA POGONA VJETROELEKTRANE U ELEKTROENERGETSKOM SUSTAVU ZASNOVANA NA SINKRONIZIRANIM MJERENJIMA
DYNAMIC ANALYSIS OF WIND FARM OPERATION INTEGRATED IN POWER SYSTEM BASED ON SYNCHRONIZED MEASUREMENTS

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Sažetak: *Pouzdano i sigurno vođenje elektroenergetskog sustava (EES) ovisi o dobrom poznavanju strujno-naponskih prilika tijekom normalnih i izvanrednih pogonskih stanja. Poznavanje odziva EES-a u realnom vremenu s obzirom na dinamičke poremećaje uzrokovane karakterističnim događajima, posebno je važno za dobro vođenje EES-a. Vjetroelektrana VE Vrataruša trenutačno je jedina vjetroelektrana priključena na prijenosnu mrežu hrvatskog EES-a. U radu je analiziran utjecaj VE Vrataruša na prijenosnu mrežu Prijenosnog područja Rijeka. Provedeni su statički proračuni (proračun tokova snaga i proračun struja kratkog spoja) te dinamička analiza (prijelazne pojave), prilikom čega su obuhvaćena normalna, izvanredna i havarijska pogonska stanja te njihov utjecaj na rad zaštite i stabilnost sustava. Kao podloga za analizu poslužio je matematički model EES-a PrP Rijeka, zasnovan i verificiran na osnovi sinkroniziranih mjerenja fazora napona i struje.*

Ključne riječi:
– sinkronizirana mjerenja
– dinamičko modeliranje
– vjetroelektrana
– diferencijalna zaštita
– fazor
– uređaj za sinkronizirano mjerenje fazora

Abstract: *Reliable and safe control of the power system is based on knowing current and voltage conditions during normal and irregular states. Real time dynamic disturbance responses, caused by characteristic events, are especially important. Wind farm Vrataruša is currently the only wind farm connected to the Croatian transmission system. This paper focuses on the impact of the wind farm Vrataruša on the system in the transmission area Rijeka. Static calculations (power flow calculation and short circuit current calculation) and dynamic analyses (transient phenomena) comprise normal, irregular and outage operational states, as well as their impact on a protection system and on overall power system stability. Analyses are based on a mathematical model of the transmission system area Rijeka, verified by synchronized voltage and current phasor measurements.*

Keywords:
– synchronized measurements
– dynamic modeling
– wind farm
– differential protection
– phasor
– PMU

1. UVOD

U elektroenergetskom sustavu (EES) Republike Hrvatske u zadnjih su 5 godina ugrađeni uređaji za sinkronizirano mjerenje – *Phasor Measurement Unit* (PMU) te je time ostvareno mjerenje fazora napona i struje u pojedinim točkama prijenosnog sustava. Nakon ugradnje PMU uređaja u 400 kV prijenosnu mrežu ostvarene su mnogobrojne prednosti prilikom vođenja i nadzora EES-a u realnom vremenu. Dobivena mjerenja fazora omogućuju izradu boljeg modela EES-a te je time moguće dobiti bolju sliku stanja EES-a prilikom simulacije karakterističnih pogonskih događaja.
Izgradnjom i priključkom novih izvora (vjetroelektrana VE Vrataruša) na postojeći EES Prijenosnog područja Rijeka (PrP Rijeka) te specifičnim vezama ostalih izvora unutar PrP Rijeka moguća su nova pogonska stanja koja je potrebno analizirati u svrhu dobrog poznavanja rada EES-a PrP Rijeka.
U ovoj je analizi izrađen matematički model EES-a PrP Rijeka, zasnovan i verificiran na sinkroniziranim mjerenjima fazora napona i struje. Na osnovi matematičkog modela analizirana su normalna, izvanredna i havarijska pogonska stanja, kao i njihov utjecaj na rad zaštite i stabilnost sustava. Predmetna analiza obuhvaća simulaciju dinamičkih promjena (prolazni i trajni kratki spojevi, ispadi vodova, ispadi elektrana, promjene opterećenja i njihanje snage) u kritičnim točkama EES-a PrP Rijeka.

1. INTRODUCTION

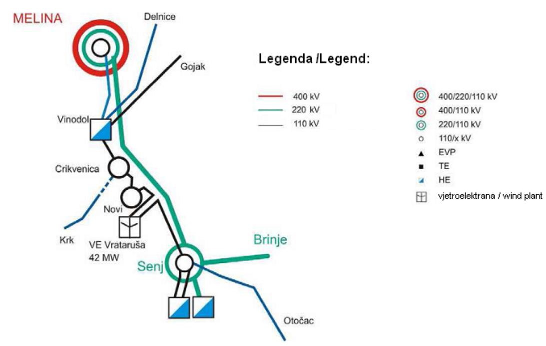
Phasor measurement units (PMUs) have been successfully deployed in the Croatian transmission system over the last 5 years. Synchronized current and voltage phasor measurements from certain points of the transmission system have been collected and analyzed. After the PMUs had been implemented in the 400 kV transmission system, several benefits, regarding real time monitoring and control, were gained. The developed power system mathematical model is based on synchronized phasor measurements. It gives better system overview during simulation of the characteristic operational events.
New operational states are derived by construction and connection of the wind farm Vrataruša to the existing transmission system, as well as by specific connections of the existing power plants. These states have to be recognized and analyzed in order to understand the power system operation in the transmission area Rijeka.
The analysis is based on the mathematical model of the power system in the transmission area Rijeka, verified by synchronized voltage and current phasor measurements. Normal, transient and faulted operational states, as well as their impact on system protection and overall power system stability, were analyzed. Simulation of dynamic changes in the critical points of the power system (passing and permanent short circuits, lines and power plant outages, load changes and power oscillations) has also been carried out.

2. PRIJENOSNI SUSTAV PRIJENOSNOG PODRUČJA PrP RIJEKA

Na slici 1 posebno je istaknuta VE Vrataruša koja je trenutačno jedina vjetroelektrana priključena na 110 kV prijenosnu mrežu hrvatskog EES-a, stoga je zanimljiva za promatranje i analizu. Najvažnija cjelina ovoga rada bavi se utjecajem VE Vrataruša na prijenosnu mrežu i temelji se na statičkim i dinamičkim analizama strujnih i naponskih prilika u dijelu sustava oko VE Vrataruša.

2. POWER SYSTEM IN THE TRANSMISSION AREA RIJEKA

Figure 1 highlights the wind farm Vrataruša, which is interesting for the analysis, as it is currently the only wind farm connected to the 110 kV Croatian transmission system. The major part of this work, which analyses the impact of the wind farm on the transmission system, is based on the static and dynamic current and voltage conditions in the wind farm Vrataruša surroundings.



Slika 1. VE Vrataruša u prijenosnoj mreži PrP Rijeka
Figure 1. The wind farm Vrataruša in the transmission area Rijeka

Prilikom analize kao referentno čvorište uzeta je TS Melina (400/220/110 kV). U njoj su smještena dva transformatora 400/220 kV, svaki snage 400 MVA te dva transformatora 220/110 kV pojedinačnih snaga 150 MVA. Na 400 kV naponskoj razini Melina je povezana sa zagrebačkim područjem (TS Tumbri), dalmatinskim zaleđem (RHE Velebit) te sa Slovenijom (TS Divača). Osim u napajanju tog dijela EES Hrvatske, TS Melina sudjeluje i u razmjenama snaga (energija) između EES srednje Europe (Mađarska, Slovačka, Češka, Poljska, Ukrajina), EES Hrvatske, EES Slovenije i EES Italije. Na 220 kV naponskoj razini TS Melina služi za prihvat proizvodnje TE Rijeka, a povezana je i s TS Pehlin, Plomin i Senj. U prijenosnoj mreži na razmatranom dijelu PrP Rijeka svi postojeći i planirani prijenosni vodovi nadzemnog su karaktera, osim vodova koji povezuju otoke.

Druga važna pojna točka mreže je TS Pehlin (220/110/35 kV) s dva transformatora 220/110 kV po 150 MVA te tri transformatora 110/35 kV snaga po 40 MVA. Na 220 kV naponskoj razini TS Pehlin povezana je s TE Plomin, TS Melina i TS Divača u Sloveniji. Preko Pehlina napajaju se riječko i opatijsko područje električnom energijom, dok se preko 220 kV mreže snaga prenosi u Sloveniju i dalje u Italiju (DV 220 kV Divača – Padriciano). Na TS Senj (220/110 kV) priključena su dva agregata HE Senj na 110 kV mrežu te jedan agregat na 220 kV mrežu. Rasklopišta 220 kV i 110 kV povezana su jednim transformatorom 220/110 kV. Sa 110 kV sabirnica napaja se i distributivna potrošnja grada Senja i okolice.

A substation Melina (400/220/110 kV), with two 400/200 kV transformers (2x400 MVA) and two 220/110 kV transformers (2x150 MVA), was used as a slack bus during the analysis. At the 400 kV level, the substation Melina is connected with the transmission area Zagreb (the substation Tumbri), Dalmatia (the reversible hydro power plant Velebit) and Slovenia (the substation Divača). Besides supplying the surrounding transmission area, the substation Melina participates in the power (energy) exchange process between the central European (Hungary, Slovakia, Czech Republic, Poland, Ukraine) and Croatian, Slovenian and Italian power systems. At the 220 kV level, the substation Melina accepts production of the thermal power plant Rijeka and it is connected with the substations Pehlin, Plomin and Senj. In the transmission area Rijeka, all the existing and planned lines are overhead; exceptions are the lines connecting the islands.

The substation Pehlin (220/110/35 kV) is the second important node, with two 220/110 kV (2x150 MVA) transformers and three 110/35 kV transformers (3x40 MVA). At the 220 kV level, it is connected with the thermo power plant Plomin and the substations Melina and Divača. The substation Pehlin is used for the energy supply of Rijeka and Opatija, while the 220 kV system is used for energy transfer to Slovenia and Italy (the 220 kV line Divača – Padriciano). In the substation Senj (220/110 kV) there are the two generators connected to the 110 kV and one to the 220 kV network. The 220 kV and 110 kV levels are connected via one 220/110 kV transformer. The 110 kV buses are used for the energy supply of the city of Senj and its surroundings.

3. MATEMATIČKI MODEL PRIJENOSNOG SUSTAVA ZASNOVAN NA SINKRONIZIRANIM MJERENJIMA

3.1. Sistemski nadzor

Zajednička koordinacija i implementacija digitalne tehnologije sekundarnih sustava, telekomunikacijske tehnologije i Ethernet tehnologije unutar informatičkog sustava EES-a upućuje na nova tehnička rješenja nadzora i vođenja EES-a. Jedno od takvih rješenja je i sistemski nadzor, odnosno *Wide Area Monitoring* – WAM.

Sistemski nadzor nalazi svoju primjenu u prepoznavanju prijelaznih poremećaja. Osobitosti i karakteristike sistemskog nadzora omogućavaju u prvom redu uvid u pogonsko stanje EES-a u realnom vremenu.

3. MATHEMATICAL MODEL OF THE TRANSMISSION SYSTEM BASED ON SYNCHRONIZED MEASUREMENTS

3.1. Wide area monitoring

Mutual coordination and deployment of several complementary parts (a secondary system digital technology, telecommunication technology and Ethernet technology) into an ICT system, leads to new concepts of power system monitoring and control. One of such solutions is known as *Wide Area Monitoring* – WAM.

The Wide Area Monitoring system is highly applicable in transient disturbances recognition. The main advantage of the Wide Area Monitoring over a traditional system is power system real time monitoring.

3.2. Sistemski nadzor EES-a Republike Hrvatske

U sustavu za sistemski nadzor EES-a (WAM) u HEP-OPS-u obuhvaćeni su PMU-uređaji u važnim čvorištima 400kV i 220kV prijenosne mreže. Sistemski nadzor zasnovan na sinkroniziranim mjerenjima sastoji se od:

- 14 PMU-uređaja ugrađenih u određena vodna polja svih 400kV i dijela 220kV trafostanica HEP – OPS sustava,
- programske podrške s funkcijom nadzora,
- telekomunikacijske veze za povezivanje PMU-uređaja s računalima za prikupljanje i obradu sinkrofazorskih podataka.

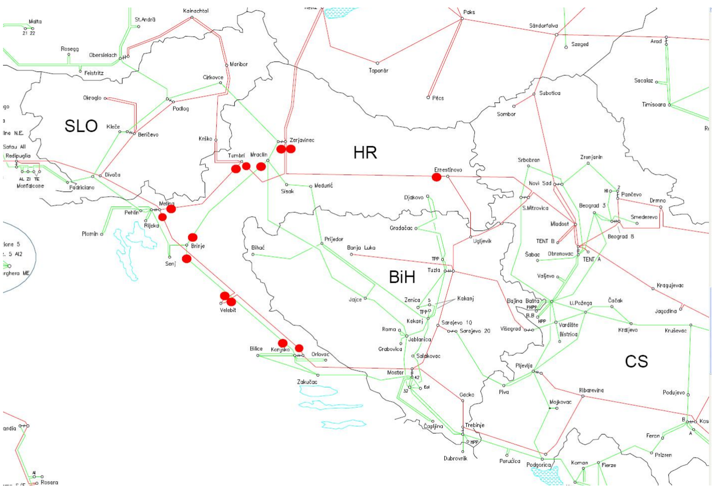
PMU-uređaji čine osnovu sustava za sistemski nadzor, a pripadaju uređajima sekundarne opreme s jedinstvenom funkcijom pridjeljivanja vremenske oznake preko GPS sinkronizacije svakom mjerenom fazoru napona i struje. Mjereni se podatak putem telekomunikacijskih veza šalje u središnji poslužitelj u sinkrofazorskom formatu (IEEE C37.118 ili IEEE 1344 opcionalno). Sinkrofazorski format napona (struje) sadrži direktnu komponentu mjerenog napona (struje) osnovne frekvencije. Broj uzoraka fazora u periodi podešen je na 50 uzoraka u sekundi (Ts = 20 ms). PMU-uređaji u HEP-OPS sustavu ugrađeni su na lokacije prikazane slikom 2.

3.2. The WAM system in the Croatian power system

The WAM system in HEP-OPS (Croatian Transmission System Operator) includes the PMUs at important 400 kV and 220 kV nodes. The Wide Area Monitoring system based on synchronized measurements comprises:

- 14 PMUs deployed at all the 400 kV and at part of the HEP – OPS 220 kV substation line fields,
- software with monitoring functionality,
- telecommunication links for the PMUs and server computers connection and synchrophasor data acquisition and processing.

The synchronized measurement units are the basis for the Wide Area Monitoring system. The PMUs are the secondary system units with a unique function of adding a time stamp to every measured voltage and current phasor by using GPS synchronization. Measured data is converted into synchrophasor format (IEEE C37.118 or IEEE 1344 optionally) and via telecommunication links sent into the central computer. The synchrophasor format contains a direct basic frequency component of measured voltage (current). The number of phasor samples in one period is set to 50 samples per second (Ts = 20 ms). The PMUs in the HEP-OPS system are deployed at locations presented in Figure 2.



Slika 2. Lokacija PMU-uređaja ugrađenih u EES Republike Hrvatske
Figure 2. The location of the PMUs deployed in the Croatian power system

3.3. Korištenje sinkroniziranih mjerenja za dinamičko modeliranje EES-a

Sistemski nadzor primjenjuje se u vođenju EES-a Republike Hrvatske, s implementiranim skupom funkcija za pomoć pri donošenju odluka operaterima/dispečerima (DSS). Analize su pokazale kako je dispečerima potrebno omogućiti bolji uvid u stanje u EES-u kod havarijskih stanja, odnosno želi se

3.3. Dynamic power system modeling based on the synchronized measurements

The Wide Area Monitoring system has been applied to the Croatian power system control system, with operator/dispatcher Decision Support System (DSS) functions deployed. The analyses have shown that the dispatchers need to have clearer insight of the power system during the faulted states, in order to avoid tunnel

po svaku cijenu izbjeći tzv. tunelski efekt pri donošenju odluka operatora.
Za razliku od tradicionalnih sustava vođenja EES-a, gdje stanična računala (RTU-jedinice) u elektroenergetskim objektima uzorkuju efektivne vrijednosti napona i struja, sistemski nadzor uzorkuje vektore napona i struje prikupljenih pomoću PMU-uređaja s određenih lokacija u EES-u i omogućava uvid u pogonsko stanje u EES-u u realnom vremenu.
Fazorska mjerenja u čvorištima EES-a predstavljaju znatnu pomoć u dobivanju dinamičkog pogleda na EES. Veliku ulogu u tom procesu imaju algoritmi za procjenu stabilnosti EES-a, koji koriste fazore kao ulazne podatke te kao rezultat prikazuju stanje EES-a, što povećava učinkovitost rada dispečera. Prilikom izrade matematičkog modela prijenosnog sustava korištena su arhivirana sinkronizirana mjerenja fazora napona i struje u čvorištima gdje su ugrađeni PMU-uređaji. Nakon izrade matematičkog modela EES-a za potrebe dinamičke analize, bilo je potrebno provesti njegovu verifikaciju. Na osnovi arhiviranih sinkroniziranih mjerenja za poznate događaje u sustavu provedene su simulacije pomoću razvijenoga matematičkog modela. Razmatrani su uglavnom događaji koji su opisivali normalna, ali različita pogonska stanja u dijelu prijenosnog područja PrP Rijeka. Na osnovi usporedbe fazora napona i struja, SCADA (*Supervisory Control And Data Acquisition*) mjerenja te tokova snaga dobivenih simulacijom izvršeno je podešavanje i verifikacija točnosti razvijenoga matematičkog modela EES-a PrP Rijeka [1-7].

4. PRORAČUN TOKOVA SNAGA

4.1. Rezultati proračuna tokova snaga

Proračuni tokova snaga provedeni su za cjelokupnu prijenosnu mrežu PrP Rijeka te su analizirana pogonska stanja koja u najvećoj mjeri utječu na analizirani dio 110 kV prijenosne mreže u okolini VE Vrataruša [10].
Prilikom proračuna tokova snaga pretpostavljena su najveća opterećenja, budući da se u tom slučaju očekuju ekstremne vrijednosti u prijenosnoj mreži. Također su analizirana stanja kada su u pogonu termoelektrane (TE Plomin 1, TE Plomin 2 i TE Rijeka) te hidroelektrana HE Rijeka s oba generatora.
Uz navedene pretpostavke, koje čine osnovno pogonsko stanje, razrađeno je više karakterističnih scenarija koji mogu dovesti do različitih strujno-naponskih prilika u dijelu analizirane prijenosne mreže PrP Rijeka, a samim time su i mjerodavni za određivanje parametara potrebnih za podešavanje relejne zaštite. Razmatrane su prilike različitog rada generatora u elektranama – HE Senj i HE Vinodol, kao i ispad pojedinih vodova.

effect.
In the traditional control systems, a remote terminal unit (RTU), located at the object, is used for sampling the RMS voltage and current values. On the other hand, the Wide Area Monitoring system gives the real time power system overview by processing the voltage and current phasors, measured by the synchronized measurement units, which are deployed at the significant power system nodes.
The phasor measurements from the power system nodes play a significant role in getting the dynamic power system overview. An important part of this process is power system stability calculation, which uses the phasors as input data and as a result displays the power system overview, increasing the dispatcher efficiency.
For the mathematical model of the transmission system, the archived synchronized current and voltage phasor measurements, from PMU deployment nodes, as well as the Supervisory Control And Data Acquisition (SCADA) system measurements, were used. After the power system mathematical model for the purpose of dynamic analysis had been built, it had to be verified. Using the developed mathematical model, simulations based on the archived synchronized measurements for the known power system events were carried out. The events describing normal but different operational states in the transmission area Rijeka were simulated. After the current and voltage phasors, the power flow simulation results and the measured values had been compared; the developed mathematical model of the power system in the transmission area Rijeka was finely tuned and finally verified [1-7].

4. POWER FLOW CALCULATION

4.1. Power flow calculation results

The power flow calculations were carried out for the whole transmission area Rijeka. Major focus was on those operational states that most influence the analyzed part of the 110 kV transmission system surrounding the wind farm Vrataruša [10].
During power flow calculation, maximum loads were assumed, as extreme values in the transmission system were then expected. The analyses also included operational states with the thermal power plants (Plomin 1, Plomin 2 and Rijeka), as well as both generators in the hydro power plant in operation in Rijeka.
Besides the given assumptions, which form the basic operational state, several characteristic scenarios, which can cause different current and voltage conditions in the part of the analyzed system, were considered. These scenarios are also relevant for the protection settings. Different combinations of the generators in operation in the hydro power plants Senj and Vinodol, as well as certain lines outages, were discussed.

Tablica 1. Scenariji mjerodavni za proračun tokova snaga
Table 1. Scenarios mandatory for the power flow calculation

VE VRATARUŠA	Ispad elementa Outaged element	Uang(Crik)	Uang(Senj)	Uang(Senj) – Uang(Crik)	Radna snaga na vodu Active power on line Vrataruša – Crikvenica
2 ASM 6 MW	Vod / Line Senj - Melina 220 kV	0,68°	6,43°	5,75°	P=76 MW
14 ASM 42 MW	Vod / Line Senj - Melina 220 kV	1,22°	7,59°	6,37°	P=96 MW
2 ASM 6 MW	Transformator / Transformer Senj 220/110 kV	1,53°	9,59°	8,06°	P=103 MW
14 ASM 42 MW	Transformator / Transformer Senj 220/110 kV	2,38°	11,86°	9,48°	P=133 MW

4.2. Analiza rezultata proračuna tokova snaga

Analizom rezultata proračuna tokova snaga utvrđeno je da je moguća značajnija razlika kutova napona, a time i struja između TS Crikvenica i TS Senj ako je u punom pogonu VE Vrataruša, HE Senj, dok je izvan pogona HE Vinodol, a posebice u slučaju ispada 220 kV prijenosnog voda Melina – Senj. U tom slučaju moguće je i preopterećenje 110 kV prijenosnog voda Crikvenica – Vrataruša. Također, što se tiče razlike kutova napona između TS Crikvenica i TS Senj i preopterećenja 110 kV prijenosnog voda Crikvenica – Vrataruša, nepovoljan je slučaj ispada transformatora 220/110 kV u TS Senj. Treba istaknuti i činjenicu da se smanjivanjem proizvodnje u VE Vrataruša razlika u kutovima napona između TS Crikvenica i TS Senj također smanjuje. Slika 3 prikazuje vezu razlike kutova na prijenosnom 110 kV vodu Crikvenica – Vrataruša i radne snage na vodu, povezanih sljedećim izrazom:

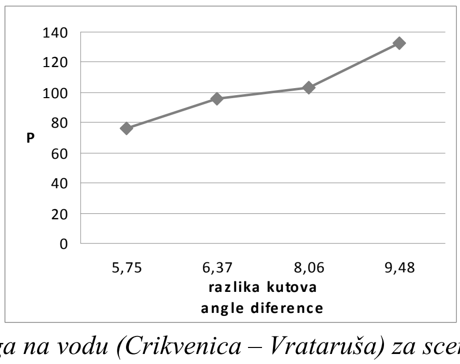
4.2. Power flow calculation results analysis

The power flow calculation analysis points out the possibility of a significant voltages (currents) angle difference between the substations Crikvenica and Senj, when the wind farm Vrataruša and the hydro power plant Senj are fully in operation and the hydro power plant Vinodol is not in operation. Considering the angle difference, unfavorable cases are the 220 kV transmission line Melina – Senj outage and the 220/110 kV transformer outage in the substation Senj. These two cases result in the significant angle difference between the substations, and the line Crikvenica – Vrataruša becomes overloaded. An important observation gained from the several simulations is that the wind farm Vrataruša production shedding consequently decreases the angle difference. Figure 3 shows the dependence of the 110 kV line Crikvenica – Vrataruša angle difference and the active power, expressed as:

$$P = \frac{V_S \cdot V_R}{X_L} \cdot \sin(Ang_R - Ang_S)\,. \quad (1)$$

Gdje su:
- V_S, V_R – naponi na krajevima voda,
- Ang_R, Ang_S – kutovi na krajevima voda,
- $(Ang_R - Ang_S)$ – razlika kutova,
- X_L – reaktancija voda,
- P – radna snaga na vodu.

Where:
- V_S, V_R – line end voltages,
- Ang_R, Ang_S – line end angles,
- $(Ang_R - Ang_S)$ – angle difference,
- X_L – line reactance,
- P – active power.



Slika 3. Razlika kutova i radna snaga na vodu (Crikvenica – Vrataruša) za scenarije prikazane tablicom 1
Figure 3. Angle difference and active power on the line (Crikvenica – Vrataruša) for the scenarios in Table 1

5. PRORAČUN STRUJA KRATKOG SPOJA

5.1. Rezultati proračuna struja kratkog spoja

Proračuni struja kratkog spoja (jednopolni i tropolni kratki spoj) za prijenosnu mrežu PrP Rijeka provedeni su s obzirom na pogonska stanja kada su u pogonu generatori u elektranama u okolici VE Vrataruša (HE Senj, HE Vinodol, HE Rijeka, HE Sklope, TE Rijeka, TE Plomin 1, TE Plomin 2), te za različita pogonska stanja VE Vrataruša [11-12].

5.2. Analiza proračuna struja kratkog spoja

Analizom rezultata proračuna struja kratkog spoja uočen je blagi utjecaj VE Vrataruša na struje kratkog spoja, koji se opaža jedino u čvorištima HE Senj, Crikvenica i Vinodol.

6. DINAMIČKA ANALIZA ELEKTROENERGETSKOG SUSTAVA PrP RIJEKA

Istraživanjima provedenim u sklopu ovog rada nastoji se pridonijeti analizi značajki pogona VE Vrataruša s asinkronim generatorima, i to sa stajališta prijelaznih pojava koje je moguće očekivati u karakterističnim točkama pogona vjetroelektrane [13-14]. Pri tome su razmatranja ograničena na dugotrajnije dinamičke analize rada VE Vrataruša. Budući da prijelazna stabilnost može predstavljati vrlo izražen problem EES-a [15-16], analize se provode sa stajališta zaštite prilikom nastanka pogonskog događaja. Tako je prijelazna stabilnost EES-a PrP Rijeka analizirana sa stajališta konkretnih, mogućih poremećaja pogona, a ne kritičnih vremena kako je to uobičajeno u fazi planiranja EES-a.
Analizirano je ponašanje EES-a [17-20] nakon nastanka mogućih, realnih prijelaznih pojava koje mogu nastati u bližoj okolini lokacije VE Vrataruša.

6.1. Opis analiziranih pogonskih stanja

Na osnovi navedenog provedene su simulacije dinamičkih promjena EES-a PrP Rijeka u okolici lokacije VE Vrataruša prilikom sljedećih karakterističnih pogonskih stanja:

- prolazni kratki spoj,
- trajni kratki spoj,
- ispadi vodova i elektrana,
- promjena opterećenja.

U tablici 2 prikazani su neki od scenarija pogonskih događaja za koje je provedena dinamička analiza EES-a PrP Rijeka u okolici lokacije VE Vrataruša (u pogonu HE Senj, HE Rijeka, HE Sklope, TE Rijeka, TE Plomin 1, TE Plomin 2).

5. SHORT CIRCUIT CALCULATION

5.1. Short circuit calculation results

Short circuit calculations (one phase and three phases) for the transmission system of the Rijeka area were calculated for the various operational states of the wind farm Vrataruša, with the generators in hydro power plants (Senj, Vinodol, Rijeka, Sklope) and thermal power plants (Rijeka, Plomin 1, Plomin 2) in operation [11-12].

5.2. Analysis of the short circuit calculation

Analysis of the short circuit calculation results points out a slight impact of the wind farm Vrataruša on the short circuit currents, which can be noticed only at the nodes Senj, Crikvenica and Vinodol.

6. DYNAMIC ANALYSIS OF THE TRANSMISSION SYSTEM RIJEKA AREA

The intention of the research carried out in this paper is the contribution to the analysis of the wind farm Vrataruša and its induction generators operation from the transient phenomena point of view, which can be expected in the characteristic operational points [13-14]. In this analysis, all the observations were constrained to a stage of transient stability. The final result is a long-term dynamic analysis of the wind farm Vrataruša. As the transient stability can represent a significant problem for the power system [15-16], analyses were conducted from the protection point of view. Therefore, the transient stability of the power system in the transmission area Rijeka was analyzed for possible disturbances, instead of critical times, as one does in the planning phase.
Also, after the transient phenomena had occurred, the power system operation in the wind farm Vrataruša surroundings was analyzed [17-20].

6.1. Description of the analyzed operational states

Based on the above, the dynamic changes simulations of the power system in the transmission area Rijeka, surrounding the wind farm Vrataruša were carried out. Characteristic operational states:

- transient short circuit,
- short circuit,
- lines and power plants outages,
- load changes.

Table 2 gives some of the scenarios for which the dynamic analysis has been carried out, with the focus on the wind farm Vrataruša and its surroundings (in operation hydro power plants: Senj, Rijeka, Sklope; thermal plants: Rijeka, Plomin 1, Plomin 2).

Tablica 2. Scenariji pogonskih događaja mjerodavnih za dinamičku analizu
Table 2. Scenarios mandatory for the dynamic analysis

Scenarij Scenario	Generatori u Generators in VE VRATARUŠA	Poseban događaj Special Event
1	/	Trajni kratki spoj na vodu Vrataruša – Crikvenica; Ispad voda The permanent short circit on the line Vrataruša – Crikvenica, Line outage
2	14 ASM 42 MW	Trajni kratki spoj na vodu Vrataruša – Crikvenica; Ispad voda The permanent short circit on the line Vrataruša – Crikvenica, Line outage
3	14 ASM 42 MW	Prolazni kratki spoj na vodu Vrataruša – Crikvenica; Djelovanje APU-a u 1 s The transient short circit on the line Vrataruša – Crikvenica, Recloser in 1 s
4	14 ASM 42 MW	Ispad HE Senj G1 i G2 The hydro plant Senj G1 and G2 outage
5	14 ASM 42 MW	Ispad VE Vrataruša The wind farm Vrataruša outage
6	14 ASM 42 MW	Ispad 220 kV voda Melina – Senj The 220 kV line Melina – Senj outage

6.2. Analiza odziva EES-a PrP Rijeka na dinamičke poremećaje u sustavu

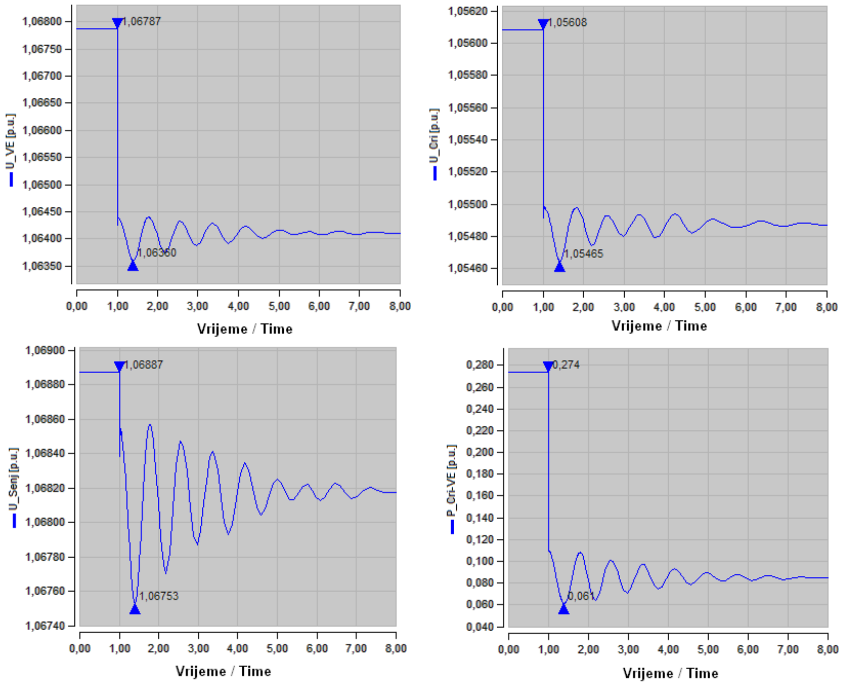
S aspekta stabilnosti može se zaključiti da većina analiziranih pogonskih događaja ne narušava stabilnost elektroenergetskog sustava. Rezultati dinamičke simulacije provedene za većinu pogonskih događaja pokazuju da poremećaj nije izazvao veće naponske oscilacije, odnosno oscilogram napona u karakterističnim čvorištima pokazuje aperiodsku pojavu manje amplitude napona koja završava unutar intervala 3-12 sekundi. Pogonski događaj 1, odnosno trajni tropolni kratki spoj na 110 kV prijenosnom vodu Crikvenica – VE Vrataruša te ispad tog voda uslijed djelovanja zaštite pokazuje oscilacije napona u karakterističnim čvorištima manje amplitude u trajanju do 2 s ako je VE Vrataruša izvan pogona. Isti događaj s punim pogonom VE Vrataruša (pogonski događaj 2) prikazuje teže pogonsko stanje za EES, odnosno aperiodski odziv napona u trajanju 60 s i veće amplitude. Posebno je zanimljiv pogonski događaj 5, odnosno ispad VE Vrataruša nakon što je bila u pogonu s maksimalnom snagom (42 MW). Rezultat simulacije je oscilatorni odziv napona i snage na 110 kV prijenosnom vodu Crikvenica – Vrataruša sa značajnim amplitudama oscilacija u trajanju 7 s, slika 4.

Navedeni komentari rezultata dinamičke analize s obzirom na specifične pogonske događaje mogu se iskoristiti prilikom podešavanja zaštite EES-a u okolici lokacije VE Vrataruša.

6.2. Dynamic disturbances analysis of the power system of the transmission area Rijeka

After the analyses have been carried out, it can be concluded that the majority of the analyzed operational events does not destabilize the power system. The dynamic simulation results show that the analyzed disturbances did not cause significant voltage oscillations. Voltage oscillograms in the characteristic nodes of the power system show aperiodic small magnitude oscillations, which end in the 3-12 seconds time interval. Operational event #1 is the case in which the wind farm Vrataruša is out of operation. The simulation of the permanent three phase fault on the transmission line Crikvenica – Vrataruša, followed by the line outage caused by the protection, results in 2 seconds small magnitude voltage oscillations in the observed nodes. The similar scenario, but with the wind farm Vrataruša fully in operation (#2), results in the significant oscillations, i.e. 60 seconds aperiodic response. Especially interesting seems to be the operational event #5, Figure 4. The outage of the wind farm Vrataruša after it had been fully in operation (42 MW) results in 7 seconds significant magnitude voltage and power oscillations on the 110 kV transmission line Crikvenica – Vrataruša.

The dynamic disturbances response analysis comments can be efficiently used as an input data for the protection setting in the wind farm Vrataruša surroundings.



Slika 4. Prikaz rezultata dinamičke simulacije pogonskog događaja 5 prema tablici 2
Figure 4. The dynamic simulation results of the scenario #5 in Table 2

Na slici 4 prikazane su sljedeće veličine:

- U_VE – napon na 110 kV sabirnicama u TS Vrataruša [p.u.],
- U_Cri – napon na 110 kV sabirnicama u TS Crikvenica [p.u.],
- U_Senj – napon na 110 kV sabirnicama u TS Senj [p.u.],
- P_Cri-VE – radna snaga na 110 kV prijenosnom vodu Crikvenica-VE Vrataruša [p.u.].

7. ZAKLJUČAK

Predmet ovoga rada je prikaz rezultata proračuna tokova snaga i struja kratkog spoja, s ciljem analize rezultata s obzirom na podešavanje parametara zaštite koja se ugrađuje radi štićenja elemenata EES-a u okolici lokacije VE Vrataruša. Na osnovi analize može se očekivati razlika kutova napona čvorišta 110 kV Crikvenica i Senj ako se povećava snaga koju VE Vrataruša daje u mrežu. Također treba istaknuti nepovoljan slučaj s obzirom na razlike spomenutih kutova napona u slučaju ispada 220 kV prijenosnog voda Melina – Senj i ispada transformatora 220/110 kV u TS Senj, kada dolazi do preopterećenja voda Crikvenica – Vrataruša. Podaci dobiveni analizom tokova snaga bitni su za podešavanje uzdužne diferencijalne zaštite 110 kV vodova Crikvenica – Vrataruša i Vrataruša – Senj.

Nakon navedene analize provedena je detaljna dinamička analiza odziva EES-a u okolici lokacije VE Vrataruša, s obzirom na definirane karakteristične pogonske događaje. Može se zaključiti da navedeni

Figure 4 shows the following values:

- U_VE – the 110 kV bus voltage at the substation Vrataruša [p.u.],
- U_Cri – the 110 kV bus voltage at the substation Crikvenica [p.u.],
- U_Senj – the 110 kV bus voltage at the substation Senj [p.u.],
- P_Cri-VE – the 110 kV transmission line Crikvenica-VE Vrataruša active power [p.u.].

7. CONCLUSION

The paper gives a presentation of the power flow and short circuit current calculations, so that results can be used as an input parameter for the protection setting in the wind farm Vrataruša surroundings. The results indicate that the significant voltage angle differences between the substations Crikvenica and Senj will emerge, if the output power of the wind farm Vrataruša increases. Extremely unfavorable cases are the 220 kV transmission line Melina – Senj outage and the 220/110 kV transformer Senj outage, which both result in the large angle difference between the substations and the line Crikvenica – Vrataruša becomes overloaded. Power flow analysis results are important for the 110 kV lines Crikvenica – Vrataruša and Vrataruša – Senj differential protection setting.

After the mentioned analysis, detailed dynamic analysis for the characteristic operational events in the wind farm Vrataruša surroundings was carried out. It can be concluded that the analyzed operational events would not result in power system instability, but the oscillatory pogonski događaji neće uzrokovati gubitak stabilnosti elektroenergetskog sustava, međutim zabilježeni su oscilatorni odzivi napona u čvorištima TS Senj, TS Crikvenica i TS Vrataruša te oscilacija djelatne snage u 110 kV prijenosnom vodu Crikvenica – VE Vrataruša, koji mogu utjecati na djelovanje zaštite. Vrijednosti amplituda oscilacija napona, amplituda oscilacija djelatne snage kao i trajanje oscilacija bitan su ulazni podatak prilikom analize podešenja parametara sustava zaštite na analiziranom dijelu prijenosne mreže PrP Rijeka.

voltage responses at the nodes Senj, Crikvenica, Vrataruša, as well as the 110 kV transmission line Crikvenica – Vrataruša power oscillations, which can influence on the protection, have been noticed. The voltage oscillation magnitudes, the active power oscillation magnitudes and the oscillation durations are valuable input data, which can be efficiently used for the protection setting in the analyzed part of the system in the transmission area Rijeka.

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