ANALIZA KUTNE STABILNOST SINKRONOG GENERATORA U OVISNOSTI O IZBORU SUSTAVA UZBUDE

ANALYSIS OF SYNCHRONOUS GENERATOR ANGULAR STABILITY DEPENDING ON THE CHOICE OF THE EXCITATION SYSTEM

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

The paper elaborates on the mathematical model of the electric power system with several synchronous generators and in this model the generators are presented by a non-linear mathematical model. By applying such a model, the impact of the manner of supplying the excitation system on the generator's angular stability was researched in the circumstances of occurrence of a short circuit in the network. The established model enables the analysis of the generator's stability in the circumstances of extensive disruptions in the electric power system for the case of the generator with separate excitation and the generator with self-excitation. Research results can be useful when making the decision on the choice of the generator excitation type, when renewing the existing and building new generators.

Ključne riječi: samouzbudni sustav; sinkroni generator; sustav nezavisne uzbude; višestrojni sustav
Key words: multiple-machine system; self-excitation system; separate excitation system; synchronous generator

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1 UVOD

Suvremena tehnička rješenja sustava uzbude sinkronih generatora, gdje se uzbudni namot generatora napaja preko klizno-kolutnog sustava, izvode se kao samouzbudni sustavi i sustavi s nezavisnom uzbudom. Uzbudnik samouzbudnog sustava napaja se s izvoda glavnog generatora preko uzbudnog transformatora. Uzbudnik sustava s nezavisnom uzbudom napaja se iz posebnog izvora, kod malih generatora to je najčešće generator s permanentnim magnetima, a kod većih generatora to je uzbudni sinkroni generator koji se nalazi na zajedničkoj osovini s glavnim generatorom.

Neovisno o načinu napajanja, uzbudnik se u pravilu izvodi kao punoupravljivi ispravljač u mosnom spoju.

Suvremeni regulatori napona sinkronog generatora izvode se kao digitalni mikroprocesorski regulatori s klasičnim i naprednim algoritmima i funkcijama. Važno je napomenuti da nema bitne razlike u strukturi regulatora napona za sustav s nezavisnom uzbudom i samouzbudni sustav.

Osnovna razlika među njima proizlazi iz ponašanja u pogonu pri kratkim spojevima u prijenosnoj mreži. Kod generatora s nezavisnim sustavom uzbude kratki spoj u mreži ne rezultira smanjenjem napona uzbude generatora.

Kod samouzbudnog sustava, prilikom pojave kratkog spoja u mreži, dolazi do pada napona generatora, a time i do smanjenja napona napajanja uzbude. Pri dugotrajnim kratkim spojevima, zbog pada napona uzbude, značajnije se smanjuje magnetski tok ulančen uzbudnim namotom, zbog čega se smanjuje i sinkronizacijski moment generatora. Kako se može pretpostaviti, snaga pogonskog stroja je stalna, što rezultira porastom brzine vrtnje i kuta opterećenja, a u određenim situacijama može doći i do ispada generatora iz mreže.

U ovom radu analizira se kutna stabilnost generatora/agregata sa samouzbudnim i sustavom s nezavisnom uzbudom u uvjetima pojave kratkog spoja u prijenosnoj mreži. Za odabranu prijenosnu mrežu (slika 1), koja je dio elektroenergetskog sustava (EES) u kojem se nalazi i HE Dubrovniku, provedeni su proračuni kuta opterećenja generatora pri pojavi kratkog spoja u mreži. Promatra se kut između vektora napona E'_q i vektora napona krute mreže U_m.
Proračuni su učinjeni za dva različita mjesta nastanka i za različita vremena trajanja kratkog spoja. Za potrebe analize odabran je odziv kuta

1 INTRODUCTION

Modern technical solutions regarding synchronous generator excitation systems, in case when the generator's excitation winding is supplied through the sliding ring system, are designed as self-excitation systems and separate excitation systems. The exciter of the self-excitation system is supplied from the lead of the main generator through the excitation transformer. The exciter of the separate excitation system is supplied from a special source; in case of small generators, this is most often a generator with permanent magnets and in case of bigger generators, it is an excitation synchronous generator located on the axis common with the main generator.

Regardless of the manner of supply, the exciter is normally designed as a fully-three phase full controlled bridge rectifier.

Modern synchronous generator voltage regulators are designed as digital microprocessor regulators with classical and advanced algorithms and functions. It is important to mention that no significant difference exists between the structure of the voltage regulator for the system with separate excitation, and that of the self-excitation system.

The basic difference between them arises from the behaviour in operation at short circuits in the transmission network. In the separate excitation system generators, a short circuit in the network does not result in the reduction of the generator excitation voltage.

In the self-excitation system, when a short circuit occurs in the network, there occurs a reduction in the generator voltage, and thus also a reduced excitation supply voltage. Upon long-lasting short circuits, due to the reduced excitation voltage, the magnetic flux chained by the excitation winding decreases more significantly and therefore the generator synchronization moment decreases as well. As can be assumed, the power of the drive engine is constant, which results in an increase of the rotation speed and the load angle and, in certain cases, generator's outage from the network can also occur.

The paper presents the angular stability of the generator/aggregate with the self-excitation and the separate excitation system in the circumstances of occurrence of a short circuit in the transmission network. For the selected transmission network (Figure 1), which is part of the electric power system (PS) in which the HPP Dubrovnik is located as well, calculations of the generator load angles have been performed at the occurrence of a short circuit in the network. The angle between the voltage vector E'_q and the infinite network voltage vector U_m was observed.

opterećenja jer on daje izravnu informaciju o dinamičkoj stabilnosti sinkronoga generatora pri poremećajima u elektroenergetskom sustavu.

2 MODELIRANJE ELEKTROENERGETSKOG SUSTAVA

Za analizu stabilnosti samouzbudnog sustava i sustava s nezavisnom uzbudom u uvjetima pojave kratkog spoja u prijenosnoj mreži načinjen je EES koji obuhvaća:

- matematički model sinkronog generatora u paralelnom radu u mreži,
- matematički model nezavisnog i samouzbudnog sustava uzbude i
- matematički model prijenosne mreže.

Prijenosna mreža modelirana je sustavom algebarskih jednadžbi u kojima su struje i naponi dani kao fazorske veličine, dok je sinkroni generator modeliran u vremenskom području sa sustavom diferencijalnih jednadžbi prema [1].

2.1 Matematički model sinkronog generatora

Nelinearni matematički model sinkronog generatora trećeg reda u dq-sustavu izveden je prema [2], [3] i [4] i prilagođen za simulacijske proračune. Odabrane ulazne veličine su: napon uzbude e, moment pogonskog stroja m_t i napon mreže U_m, dok su izlazne veličine: napon generatora U_G, struja generatora I_G, električka snaga P i kut opterećenja δ:

The calculations were performed for two different places of occurrence and for different time of duration of the short circuit. For the needs of the analysis, the response of the load angle was chosen because it provides direct information on the dynamic stability of the synchronous generator upon the disruptions in the electric power system

2 MODELLING THE ELECTRIC POWER SYSTEM

For the analysis of the stability of the self-excitation system and the separate excitation system in the circumstances of occurrence of a short circuit in the transmission network, an PS was generated which includes:

- the synchronous generator mathematical model in parallel operation in the network,
- the mathematical model of the separate and self-excitation systems, and
- the mathematical model of the transmission network.

The transmission network is modelled by a system of algebraic equations in which the currents and the voltages are given as phasor, while the synchronous generator is modelled in a time domain with a differential equations system according to [1].

2.1 Mathematical model of the synchronous generator

The non-linear mathematical model of the synchronous generator of the third order in the dq-system is designed according to [2], [3] and [4] and adjusted for calculations. The selected input values are: excitation voltage e, drive engine moment m_t and network voltage U_m while output values are: generator voltage U_G, generator current I_G, electric power P and load angle δ:

$$\frac{\mathrm{d}\Psi_\mathrm{f}}{\mathrm{d}t}=\frac{\omega_\mathrm{s} r_\mathrm{f}\left(x_\mathrm{d}-x_\ell\right)U_\mathrm{m}\cos(\delta)}{\omega x'_\mathrm{d} x_\mathrm{f}}+\frac{\omega_\mathrm{s} r_\mathrm{f} e}{x_\mathrm{ad}}-\frac{\omega_\mathrm{s} r_\mathrm{f}\left(x_\mathrm{d}+x_\mathrm{m}\right)\Psi_\mathrm{f}}{\left(x'_\mathrm{d}+x_\mathrm{m}\right)x_\mathrm{f}}, \tag{1}$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t}=\frac{1}{T_\mathrm{m}}\left(m_\mathrm{t}-\left(\frac{\Psi_\mathrm{f} U_\mathrm{m}\left(x_\mathrm{d}-x_1\right)\sin(\delta)}{\omega\left(x'_\mathrm{d}+x_\mathrm{m}\right)x_\mathrm{f}}+\frac{U_\mathrm{m}^2\left(x'_\mathrm{d}-x'_\mathrm{q}\right)\sin(2\delta)}{2\omega^2\left(x'_\mathrm{d}+x_\mathrm{m}\right)\left(x'_\mathrm{q}+x_\mathrm{m}\right)}\right)\right)-D(\omega-1), \tag{2}$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t}=\omega_\mathrm{s}(\omega-1)\,. \tag{3}$$

Ovisnost ulančenih tokova u d-osi i q-osi o naponu krute mreže:

The dependency of the chained flows in the d-axis and q-axis on the infinite network voltage:

$$U_{\mathrm{m}}\cos(\delta)=\omega\psi_{\mathrm{d}} \quad , \tag{4}$$

$$U_{\mathrm{m}}\sin(\delta)=-\omega\psi_{\mathrm{q}} \quad . \tag{5}$$

Sustav algebarskih jednadžbi napona, struje i djelatne snage generatora je:

The system of algebraic voltage equations, the current and active power of the generator is:

$$U_{\mathrm{d}}=\frac{x_{\mathrm{q}}U_{\mathrm{m}}\sin(\delta)}{x_{\mathrm{q}}+x_{\mathrm{m}}} \quad , \tag{6}$$

$$U_{\mathrm{q}}=\frac{x_{\mathrm{d}}^{'}U_{\mathrm{m}}\cos(\delta)}{x_{\mathrm{d}}^{'}+x_{\mathrm{m}}}+\omega \mathrm{x}_{\mathrm{m}}(x_{\mathrm{d}}-x_{1})\frac{\psi_{\mathrm{f}}}{\left(x_{\mathrm{d}}^{'}+x_{\mathrm{m}}\right)x_{\mathrm{f}}} \quad , \tag{7}$$

$$U_{\mathrm{G}}=\sqrt{U_{\mathrm{d}}^{2}+U_{\mathrm{q}}^{2}} \quad , \tag{8}$$

$$i_{\mathrm{q}}=\frac{U_{\mathrm{m}}\sin(\delta)}{\omega x_{\mathrm{m}}}-\frac{U_{\mathrm{d}}}{\omega x_{\mathrm{m}}} \quad , \tag{9}$$

$$i_{\mathrm{d}}=\frac{U_{\mathrm{q}}}{\omega x_{\mathrm{m}}}-\frac{U_{\mathrm{m}}}{\omega x_{\mathrm{m}}}\cos(\delta) \quad , \tag{10}$$

$$I_{\mathrm{G}}=\sqrt{I_{\mathrm{d}}^{2}+I_{\mathrm{q}}^{2}} \quad , \tag{11}$$

$$P=U_{\mathrm{d}}\cdot i_{\mathrm{d}}+U_{\mathrm{q}}\cdot i_{\mathrm{q}} \quad , \tag{12}$$

gdje su:

U_{m} – napon mreže,
Y_{f} – magnetski tok ulančen uzbudnim namotom,
Y_{d}, Y_{q} – ulančeni magnetski tokovi armature u d i q osi,
ω – kutna brzina,
ω_{s} – sinkrona brzina vrtnje generatora,
T_{m} – konstanta tromosti agregata,
D – koeficijent ekvivalentnog prigušenja,
x_{d} – uzdužna reaktancija armature,
x'_{d} – prijelazna uzdužna reaktancija armature,
x_{q} – poprečna reaktancija armature,
x_{m} – reaktancija do krute mreže,
r_{f} – djelatni otpor uzbudnog kruga,
x_{f} – reaktancija uzbudnog kruga,
U_{d}, U_{q} – komponente napona generatora u d-osi

whereat it is as follows:

U_{m} – network voltage,
Y_{f} – field flux linkages,
Y_{d}, Y_{q} – stator flux d and q-axis linkages,
ω – angular speed,
ω_{s} – base speed,
T_{m} – mechanical time constant,
D – damping coefficient,
x_{d} – synchronous d-axis reactance,
x'_{d} – d-axis transient reactance,
x_{q} – synchronous q-axis reactance,
x_{m} – reactance to the infinite network,
r_{f} – equivalent field winding resistance,
x_{f} – field winding reactance,
U_{d}, U_{q} – components of the generator voltage in the d-axis and the q-axis,
i_{d}, i_{q} – – armature current in d- axis and q-axis.

i q-osi,

i_d, i_q – komponente struje generatora u d-osi i q-osi

x_{ad} – reaktancija međuinduktivne veze armaturnog i uzbudnog namota u uzdužnoj osi,

x_l – rasipna reaktancija armature.

U simulacijskom proračunu, za rješavanje diferencijalnih jednadžbi (1), (2) i (3) korišten je prediktor-korektor postupak.

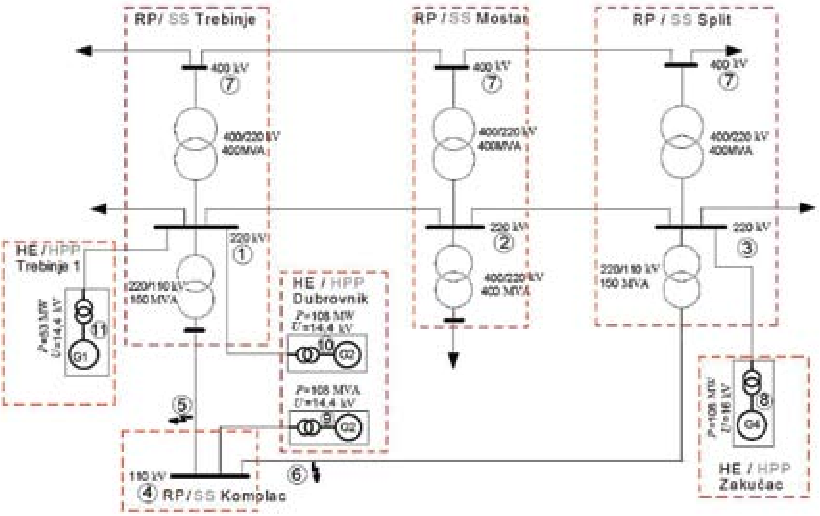
2.2 Matematički model prijenosne mreže

Matematički model je formiran za prijenosnu mrežu čija je jednopolna shema pokazana na slici 1. Mreža je dio elektroenergetskog sustava, a čine je: sinkroni generatori, transformatori, prijenosni vodovi i trošila.

In the calculations, for solving differential equations (1), (2) and (3), the predictor-corrector procedure was used.

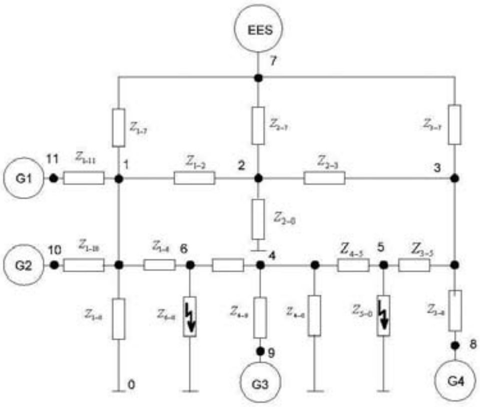
2.2 Mathematical model of the transmission network

The mathematical model is formed for the transmission network which single line diagram is shown in Figure 1. The network is part of the electric power system and it consists of: synchronous generators, transformers, transmission lines and power system devices.



Slika 1 — Jednopolna shema djela EES

Figure 1 — One-pole scheme of the part of the EPS



$Z_{1-2} = 0 + j0,2$ $\quad Z_{3-5} = 0 + j0,39$

$Z_{1-0} = 2 + j0,2$ $\quad Z_{3-7} = 0 + j0,05$

$Z_{1-6} = 0 + j0,05$ $\quad Z_{3-8} = 0 + j0,12$

$Z_{1-10} = 0 + j0,12$ $\quad Z_{3-0} = 1 + j0,1$

$Z_{1-11} = 0 + j0,12$ $\quad Z_{4-5} = 0 + j0,01$

$Z_{2-7} = 0 + j0,05$ $\quad Z_{4-6} = 0 + j0,01$

$Z_{2-3} = 0 + j0,2$ $\quad Z_{4-9} = 0 + j0,12$

$Z_{2-0} = 1 + j0,1$ $\quad Z_{4-0} = 4 + j0,4$

$Z_{5-0} = 0 + j10^3$ $\quad Z_{6-0} = 0 + j10^3$

Slika 2 — Model elektroenergetskog sustava i vrijednosti pripadnih reaktancija

Figure 2 — Electric power system model and values of the pertaining reactance

Nadomjesna shema modelirane prijenosne mreže pokazana je na slici 2, vrijednosti nadomjesnih reaktancija su normirane na bazni sustav generatora 3 (G3). Ostatak elektroenergetskog sustava, koji je na promatrani sustav spojen prijenosnim vodom od $400\ \mathrm{kV}$, nadomješten je idealnim naponskim izvorom (EES). Na slici 2 trofazni sustav nadomješten je jednofaznim direktnim sustavom, što omogućava istraživanja simetričnih pojava. Za referentno čvorište odabrana je nultočka sustava.

Stanje u mreži opisuje se primjenom I Kirchoffovog zakona i za odabranu mrežu je:

The equivalent scheme of the modelled transmission network is shown in Figure 2, the values of equivalent reactance are set to the generator's basic system 3 (G3). The rest of the electric power system, which is connected to the observed system by a $400\ \mathrm{kV}$-transmission line, is substituted by an ideal voltage source (PS). In Figure 2, the three-phase system is substituted with a single-phase direct system which enables the research of symmetrical cases. The system's zero field was chosen as the reference node.

The situation in the network is described by applying the Kirchoff's Laws and for the selected network it is:

$$\begin{aligned}
&\frac{V_1}{Z_{1-2}}+\frac{V_1}{Z_{1-6}}+\frac{V_1}{Z_{1-7}}+\frac{V_1}{Z_{1-10}}+\frac{V_1}{Z_{1-11}}+\frac{V_1}{Z_{1-0}}-\frac{V_2}{Z_{1-2}}-\frac{V_6}{Z_{1-6}}-\frac{V_7}{Z_{1-7}}-\frac{V_{10}}{Z_{1-10}}-\frac{V_{11}}{Z_{1-11}}=0\\
&\frac{V_2}{Z_{1-2}}+\frac{V_2}{Z_{1-3}}+\frac{V_2}{Z_{1-7}}+\frac{V_2}{Z_{2-0}}-\frac{V_1}{Z_{1-2}}-\frac{V_3}{Z_{1-3}}-\frac{V_7}{Z_{1-7}}=0\\
&\frac{V_3}{Z_{2-3}}+\frac{V_3}{Z_{3-5}}+\frac{V_3}{Z_{3-7}}+\frac{V_8}{Z_{3-8}}-\frac{V_2}{Z_{2-3}}-\frac{V_5}{Z_{3-5}}-\frac{V_7}{Z_{3-7}}-\frac{V_8}{Z_{3-8}}=0\\
&\frac{V_4}{Z_{4-5}}+\frac{V_4}{Z_{4-6}}+\frac{V_4}{Z_{4-9}}+\frac{V_4}{Z_{4-0}}-\frac{V_5}{Z_{4-5}}-\frac{V_6}{Z_{4-6}}-\frac{V_9}{Z_{4-9}}=0 \qquad , \\
&\frac{V_5}{Z_{3-5}}+\frac{V_5}{Z_{4-5}}+\frac{V_5}{Z_{5-0}}-\frac{V_3}{Z_{3-5}}-\frac{V_4}{Z_{4-5}}=0\\
&\frac{V_6}{Z_{1-6}}+\frac{V_6}{Z_{4-6}}+\frac{V_6}{Z_{6-0}}-\frac{V_1}{Z_{1-6}}-\frac{V_4}{Z_{4-6}}=0
\end{aligned} \tag{13}$$

gdje su čvorišta za koje su poznate vrijednosti napona:

where the nodes, for which the voltage values are known, are:

$$\begin{aligned}
&V_7=1+\mathrm{j}\cdot 0,\\
&V_8=U_{G4}\cdot \mathrm{e}^{\mathrm{j}\varphi_7},\\
&V_9=U_{G3}\cdot \mathrm{e}^{\mathrm{j}\varphi_8},\\
&V_{10}=U_{G2}\cdot \mathrm{e}^{\mathrm{j}\varphi_9},\\
&V_{11}=U_{G1}\cdot \mathrm{e}^{\mathrm{j}\varphi_{10}}.
\end{aligned} \tag{14}$$

Sustav jednadžbi (13) u matričnom obliku je:

The equation system (13) in the matrix form is:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \\ V_8 \\ V_9 \\ V_{10} \\ V_{11} \end{bmatrix} = \begin{bmatrix} Y_{1,1} & 0 & 0 & 0 & 0 & Y_{1,6} & Y_{1,7} & 0 & 0 & Y_{1,10} & Y_{1,11} \\ Y_{2,1} & Y_{2,2} & Y_{2,3} & 0 & 0 & 0 & Y_{2,7} & 0 & 0 & 0 & 0 \\ 0 & Y_{3,2} & Y_{3,3} & 0 & Y_{3,5} & 0 & 0 & Y_{3,8} & 0 & 0 & 0 \\ 0 & 0 & 0 & Y_{4,4} & Y_{4,5} & Y_{4,6} & 0 & 0 & Y_{4,9} & 0 & 0 \\ 0 & 0 & Y_{5,3} & Y_{5,4} & Y_{5,5} & 0 & 0 & 0 & 0 & 0 & 0 \\ Y_{6,1} & 0 & 0 & Y_{6,4} & 0 & Y_{6,6} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ U_{\mathrm{G}4 \cdot e^{\mathrm{j}\varphi_7}} \\ U_{\mathrm{G}3 \cdot e^{\mathrm{j}\varphi_8}} \\ U_{\mathrm{G}2 \cdot e^{\mathrm{j}\varphi_9}} \\ U_{\mathrm{G}1 \cdot e^{\mathrm{j}\varphi_{10}}} \end{bmatrix} . \qquad (15)$$

Matrica admitancija desno od znaka jednakosti u (15) formirana je iz (13) što odgovara metodi napona čvorova. Elementi na glavnoj dijagonali matrice određeni su sumom admitancija grana koje su povezane s i–tim čvorištem pa se općenito može napisati za čvorišta čiji potencijal nije poznat:

The admittance matrix right of the equation symbol in (15) is formed from (13) which matches the nodes voltage method. The elements on the main matrix diagonal are determined by the sum of the admittance of branches which are connected with the i-th node so, in general, for the nodes which potential is not known, the following can be written:

$$Y_{i,i} = \sum_{i=1}^{n} \frac{1}{Z_{i,j}} \Bigg|_{(i=j)} , \qquad (16)$$

dok su vrijednosti ostalih elemenata čiji su potencijali poznati jednaki jedinici.

while the values of the other elements, which potentials are known, are equal to zero.

Članovi izvan glavne dijagonale matrice određuju se kao negativna vrijednost vodljivosti grane mreže između čvorišta i i čvorišta j:

The terms outside the main matrix diagonal are determined as negative value of the network branch conductivity between the node i and the node j:

$$Y_{i,j} = -\frac{1}{Z_{i,j}} \Bigg|_{(i \neq j)} . \qquad (17)$$

Za izračun stanja u mreži primijenjen je Gaussov iteracijski postupak, u matematici poznat pod nazivom Jacobiev iteracijski postupak. Primjena Gaussovog postupka je nužna iz razloga što nisu poznati argumenti napona čvorišta u kojima su spojeni generatori. Za jednoznačno definiranje čvorišta u kojima su spojeni generatori (slika 2 čvorišta 8, 9, 10 i 11) potrebni su modul napona generatora $U_{\mathrm{G}n}$ i djelatna snaga generatora $P_{\mathrm{G}n}$ (indeks $\mathrm{G}n$ je redni broj generatora) koji je spojen u promatrano čvorište. Napon i snaga pojedinog generatora dobivaju se izračunom, iz matematičkog modela sinkronog generatora. Kompleksna vrijednost napona čvorišta 7, na kojega je spojen nadomješteni ekvivalent elektroenergetskog sustava, iznosi $V_7 = j \cdot 0$.

For the calculation of the situation in the network, the Gauss iterative method, known in mathematics as the Jacobi iterative procedure, was applied. The application of the Gauss method is necessary because the operators of the voltage of the nodes in which the generators are connected are not known. For an unambiguous definition of hubs in which the generators are connected (Figure 2, 8, 9, 10 and 11), the generator voltage magnitude $U_{\mathrm{G}n}$ and the active power of the generator $P_{\mathrm{G}n}$, which is connected to the observed node, are necessary (the index is the generator's ordinal number). The voltage and the power of the particular generator are obtained by calculation from the mathematical model of the synchronous generator. The complex value of node 7, to which the substitute equivalent of the electric power system is connected, amounts to $V_7 = j \cdot 0$.

U prvoj iteraciji iznosi argumenata napona generatora za čvorišta u kojima su generatori spojeni (8, 9, 10 i 11) se pretpostavljaju. Rješavanjem sustava jednadžbi (15) odrede se nepoznati iznosi potencijala ostalih čvorišta (1, 2, 3, 4, 5 i 6). Vrijednost argumenta napona generatora za svaku sljedeću iteraciju određuje se prema:

In the first iteration, the values of the generator voltage operators for the nodes in which the generators are connected (8, 9, 10 and 11) are assumed. By solving the equations system (15), unknown values of the potentials of the other hubs (1, 2, 3, 4, 5 and 6) are determined. The value of the operators of the generator voltage for each subsequent iteration is determined according to:

$$\begin{bmatrix} \varphi_8 \\ \varphi_9 \\ \varphi_{10} \\ \varphi_{11} \end{bmatrix} = \begin{bmatrix} \varphi_3 + \dfrac{P_{G4} x_{3-8}}{|U_{G4}||V_3|} \\ \varphi_4 + \dfrac{P_{G3} x_{4-9}}{|U_{G3}||V_4|} \\ \varphi_1 + \dfrac{P_{G2} x_{1-10}}{|U_{G2}||V_1|} \\ \varphi_1 + \dfrac{P_{G1} x_{1-11}}{|U_{G1}||V_1|} \end{bmatrix}, \qquad (18)$$

gdje su:

$\varphi_8, \varphi_9, \varphi_{10}, \varphi_{11}$ – kutovi fazora napona čvorišta u kojem se nalazi generator, a

$\varphi_3, \varphi_4, \varphi_1$ – kutovi fazora susjednih čvorišta, slika 2.

Nakon što se odrede kutovi fazora čvorišta u kojima su spojeni generatori (18) određuju se nove kompleksne vrijednosti napona tih čvorišta. S novim kompleksnim vrijednostima napona čvorišta (8, 9, 10 i 11) rješava se sustav jednadžbi (15). Opisani postupak se ponavlja sve dok se razlika argumenata napona čvorišta (8, 9, 10 i 11), u koraku k i koraku $(k-1)$ ne smanji na zanemarivo mali iznos $(\varphi_i(k) - \varphi_i(k-1) < 10^{-4})$.

Odabrano vrijeme diskretizacije, odnosno vremenski korak nakon kojeg se rješava jednadžba (16) i vrijeme integracije za rješavanje modela sinkronih generatora je jednako i iznosilo je $T = 0{,}005$ s. Broj iteracija do postizanja zadane točnosti $(\varphi_i(k) - \varphi_i(k-1) < 10^{-4})$ za rješavanje jednadžbe (16) iznosio je maksimalno 10 za vrijeme trajanja poremećaja, a u stacionarnom stanju broj iteracija kretao se od 1 do 2. Numerička stabilnost postupka provjerena je povećavanjem koraka integracije pri čemu je zadržana konvergentnost u rješavanju sustava jednadžbi (15) kao i numerčka stabilnost u rješavanju diferencijalnih jednadžbi matematičkog modela sinkronih generatora i sustava uzbude.

whereat it is as follows:

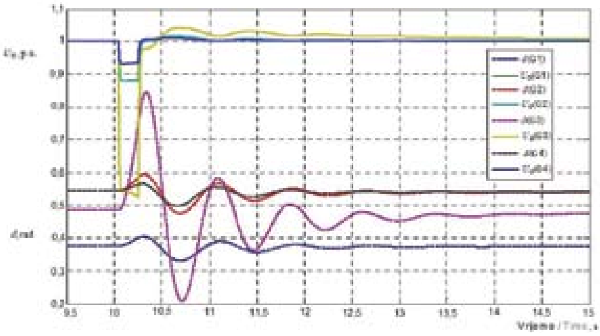
$\varphi_8, \varphi_9, \varphi_{10}, \varphi_{11}$ – voltage phasor angles of the node in which the generator is connected and

$\varphi_3, \varphi_4, \varphi_1$ – angles of the phasors of the neighbouring hubs, Figure 2.

After the determination of the phasor angles of the node in which the generators are connected (18), new complex values of the voltages of those are determined. With new complex values of the voltages of the (8, 9, 10 and 11), the equations system is solved (15). The described procedure is repeated until the difference of the operators of the voltages (8, 9, 10 and 11) in step k and step $(k-1)$ is reduced to a negligibly small value $(\varphi_i(k) - \varphi_i(k-1) < 10^{-4})$.

The selected discretization period, that is, the temporal step after which the equation (16) is solved and the period of integration for solving the synchronous generator models were equal and amounted to $T = 0{,}005$ s. The number of iterations until the achievement of the set accuracy for solving the equation (16) amounted to max. 10 for the duration of the disruption, and in steady state, the number of iterations fluctuated from 1 to 2. The numeric stability of the procedure was verified by increasing the integration steps whereat the convergent quality was kept in solving equations systems (15), as well as the numeric stability in solving differential equations of the mathematical model of the synchronous generator and the excitation system.

By applying the derived procedure, calculations



Slika 3 — Odziv napona generatora G3 i kutova opterećenja generatora G3 pri pojavi kratkog spoja u čvorištu 6 mreže na slici 2

Figure 3 — Response of the G3 generator voltage and the G3 generator load angles at the occurrence of a short circuit in hub 6 of the network from Figure 2

Primjenom razvijenog postupka proveden je simulacijski proračun odziva veličina modela sinkronih generatora pri nastanku kratkog spoja u prijenosnoj mreži. U mreži na slici 2 simulirana je pojava kratkog spoja u čvorištu 6. Kratki spoj simuliran je smanjivanjem stacionarnog iznosa impendancije $Z_{6\text{-}0} = \mathrm{j} \cdot 10^3$ na iznos $Z_{6\text{-}0} = \mathrm{j} \cdot 10^{-3}$ u trajanju od $0{,}2$ s. Rezultat simulacijskog proračuna pokazan je na slici 3. Vidljive su značajne razlike u iznosima poremećaja na generatorima zbog različite električke udaljenosti generatora od mjesta kvara. Na generatoru G3 maksimalno nadvišenje kuta opterećenja iznosilo je 180 % stacionarne vrijednosti dok je za generator G1 maksimalno nadvišenje kuta opterećenja iznosilo samo 105 % stacionarne vijednosti kuta opterećenja. Postignuta maksimalna nadvišenja kuta opterećenja odgovaraju maksimalnim propadima napona na sabirnicama generatora.

2.3 Matematički model sustava uzbude

Sustavi uzbude generatora modelirani su na temelju standardnih modela iz [6] koji se koriste za simulacijske proračune. Samozbudni sustav modeliran je prema standardnom modelu uzbudnog sustava označen kao ST1A. U ostvarenju sustava uzbude prema modelu ST1A uzbudnik je izveden kao punoupravljivi ispravljač u mosnom spoju, koji se napaja sa stezaljki sinkronog generatora preko transformatora. Struktura sustava uzbude koji je primijenjen za simulacijske proračune pokazana je na slici 4a. Standardni model ST1A je za potrebe ovog proračuna pojednostavljen tako što su isključeni stabilizacijski i kompenzacijski blokovi. Provedena pojednostavljenja nemaju znatnog utjecaja na rezultate proračuna ponašanja sinkronog generatora u uvjetima pojave kratkog spoja na mreži [4].

were undertaken of the response of the sizes of the synchronous generator models in short-circuit disturbance in the transmission network. In the network in Figure 2, the occurrence of a short circuit in node 6 was simulated. The short circuit was simulated by reducing the stationary impedance value of $Z_{6\text{-}0} = \mathrm{j} \cdot 10^3$ to the value $Z_{6\text{-}0} = \mathrm{j} \cdot 10^{-3}$ in the duration of $0{,}2$ s. Calculations result is shown in Figure 3. Significant differences are visible in the extents of the disruptions on the generators depending on the generator's varying electric distance from the place of the failure. On the G3 generator, maximum altitudes of the load angle amounted to 180 % of the stationary value, while on the G1 generator, the maximum altitudes of the load angle amounted only to 105 % of the load angle stationary value. The achieved maximum altitudes of the load angle match the maximum voltage drops on the generator's busbars.

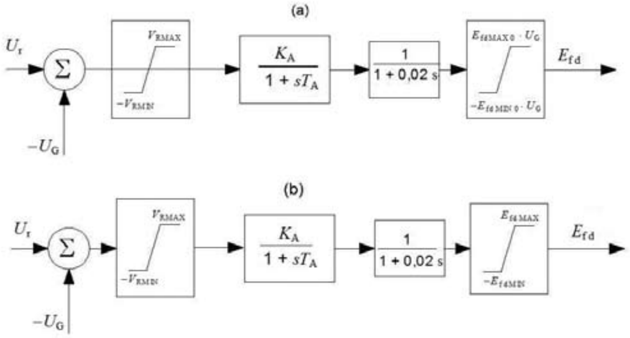
2.3 Mathematical model of the excitation system

Generator excitation systems are modelled based on standard models from [6] which are used for calculations. The self-excitation system is modelled according to the standard model of the excitation system marked as ST1A. In the execution of the excitation system according to the ST1A model, the exciter is designed as a fully controlled rectifier in a bridge connection which is supplied from the terminals of the synchronous generator through the transformer. The structure of the excitation system which was applied for calculations is shown in Figure 4a. The standard ST1A model was simplified for the needs of this calculation so as to include the stabilization and compensation blocks. The undertaken simplifications have no significant impact on the results of the calculation of the behaviour of the synchronous generator in the circumstances of occurrence of a short circuit in the network [4].

The properties of the excitation system of the ST1A

Značajke sustava uzbude tipa ST1A su pojačanje regulatora $K_A > 100$ i vremenska konstanta $T_A = 0{,}02$ s. Zbog činjenice da se uzbudnik napaja preko transformatora koji je spojen na izvode generatora ovaj sustav se izvodi s odgovarajućim forsiranjem. Utjecaj napona generatora U_G na iznos napona uzbude E_{fd} ogleda se u promjenljivom iznosu ograničenja za maksimalno mogući iznos napona uzbude. Maksimalni pozitivni odnosno negativni iznos ograničenja napona uzbude su: $E_{fdMAX} = E_{fdMAX0} \cdot U_G$, $E_{fdMIN} = -E_{fdMAX0} \cdot U_G$, gdje je E_{fdMAX0} maksimalni mogući napon uzbude određen faktorom forsiranja.

type are the gain of the regulator $K_A > 100$ and the time constant $T_A = 0{,}02$ s. Because of the fact that the exciter is supplied through the transformer which is connected to the leads of the generator, this system is designed with adequate forcing. The impact of the generator voltage U_G on the amount of the excitation voltage E_{fd} is reflected in the variable amount of limitation for the maximum possible amount of the excitation voltage. The maximum positive, that is, negative amounts of the excitation limitation are: $E_{fdMAX} = E_{fdMAX0} \cdot U_G$, $E_{fdMIN} = -E_{fdMAX0} \cdot U_G$, where E_{fdMAX0} is the maximum possible excitation voltage defined by the forcing factor.



Slika 4 — Blokovski prikaz sustava uzbude
Figure 4 — Block overview of the excitation systems

Sustav s nezavisnom uzbudom modeliran je prema preporuci [6] kao AC4A, a pokazan je na slici 4b . Uzbuda glavnog sinkronog generatora napaja se preko ispravljača sa stezaljki pomoćnog sinkronog generatora koji je ugrađen na zajedničkoj osovini s glavnim generatorom.

U ovom modelu pretpostavlja se da je napon izvora za napajanje uzbude glavnog sinkronog generatora konstantan, zanemaren je pad napona u stanju vođenja tiristora, što znači da se regulacija napona odvija u linearnom području sve dok napon uzbude ne dostigne maksimalni pozitivni odnosno negativni iznos.

S ciljem da se omogući usporedba rezultata dobivenih izračunom osnovni parametri regulatora postavljeni su na jednake iznose u samouzbudnom sustavu i sustav s nezavisno uzbudom i to: pojačanje regulatora podešeno je na $K_A = 100$, a vrijeme kašnjenje regulatora na $T_A = 0{,}02$ s .

The separate excitation system is modelled according to the recommendation [6] as AC4A and shown in Figure 4b. The excitation of the main synchronous generator is supplied through the rectifier from the terminals of the auxiliary synchronous generator which is installed on the same shaft with the main generator.

In this model, it is assumed that the voltage of the source for supplying the excitation of the main synchronous generator is constant; the voltage drop in the thyristor conduction state is neglected, and this means that voltage regulation is in a linear area all until the excitation voltage reaches either the positive, or the negative amount.

With the aim to enable the comparison of results obtained by calculation, the basic parameters of the regulator are set at equal amounts in the self-excitation system and in the separate excitation system and that being: regulator's gain is set at $K_A = 100$ and its time constant is set at $T_A = 0{,}02$ s .

3 CALCULATION RESULTS

3 REZULTATI PRORAČUNA

Rezultati proračuna kuta opterećenja generatora pri pojavi kratkog spoja na mreži u čvorištu 6 pokazani su na slikama 5 i 6 dok su na slikama 7 i 8 pokazani rezultati dobiveni pri pojavi kratkog spoja na mreži u čvorištu 5. U oba slučaja proračun je napravljen za sustav s nezavisnom uzbudom i samouzbudni sustav u potpuno jednakim pogonskim uvjetima. Djelatne snage sinkronih generatora (izražene u pu generatora G3) koji su uključeni u modelirani elektroenergetski sustav su redom:

$P_{G1} = 0{,}6\ \mathrm{p \cdot u}$; $P_{G2} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G3} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G4} = 0{,}9\ \mathrm{p \cdot u}$

Prva grupa proračuna provedena je u uvjetima pojave kratkog spoja u čvorištu 6 pri čemu je kratki spoj simuliran smanjivanjem reaktancije koja spaja čvorište 6 s referentnim čvorištem 0 (slika 2) na vrijednost od $Z_{6\text{–}0} = \mathrm{j} \cdot 10^{-3}$. Uspoređeni su odzivi kuta opterećenja δ generatora G3, za različita vremena trajanja kratkog spoja (slike 5 i 6).

Najprije je odabrano vrijeme trajanja kratkog spoja $T_k = 100$ ms, što odgovara tipičnom vremenu prorade zaštite voda u prvoj zoni, zatim je vrijeme trajanja kratkog spoja povećano je na $T_k = 200$ ms i nakon toga proračun je proveden za vrijeme trajanja kratkog spoja $T_k = 400$ ms što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti.

Rezultati izračuna pokazani su na slici 5a dok su na slici 5b dane razlike kuta opterećenja $\Delta\delta$ generatora G3 s nezavisnom uzbudom i samouzbudom za odabrana vremena trajanja kratkog spoja.

Results of the calculation of the generator load angle in short-circuit disturbance on the network in node 6 are shown in Figures 5 and 6, while Figures 7 and 9 show the results obtained in short-circuit disturbance on the network in node 5. In both cases, the calculation was performed for the system with separate excitation and the self-excitation system in in same conditions. Active powers of synchronous generators (stated in G3 generator pu) which are included in the modelled electric power system are consecutively as follows:

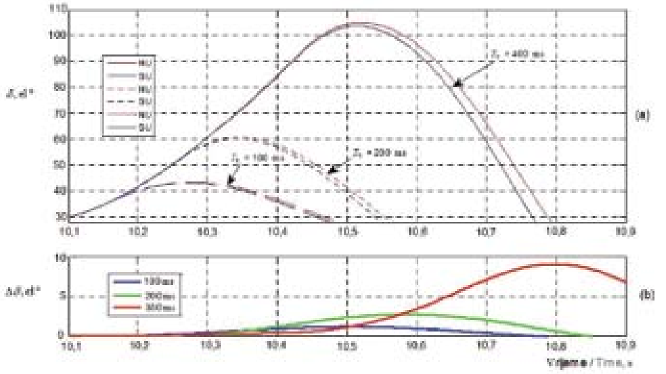
$P_{G1} = 0{,}6\ \mathrm{p \cdot u}$; $P_{G2} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G3} = 0{,}9\ \mathrm{p \cdot u}$; $P_{G4} = 0{,}9\ \mathrm{p \cdot u}$

The first calculation group was designed in the conditions of occurrence of a short circuit in node 6 whereat the short circuit was simulated by reducing the reactance which connects node 6 to the reference node 0 (Figure 2) to the amount of $Z_{6\text{–}0} = \mathrm{j} \cdot 10^{-3}$. Responses of the load angle δ of the G3 generator were compared for different durations of the short circuit (Figures 5 and 6).

At first, the duration of the short circuit $T_k = 100$ ms was chosen which matches the typical time of the tripping of the line in the first zone, then the duration of the short circuit was increased to $T_k = 200$ ms and after that, the calculation was performed for the duration of the short circuit $T_k = 400$ ms which matches the critical time of duration of the short circuit according to the transitive stability criterion.

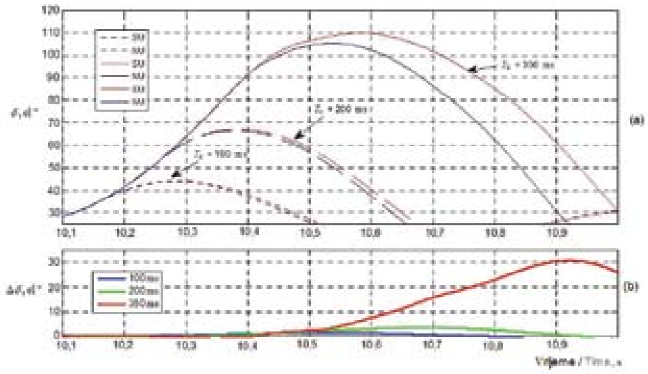
Calculation results were shown in Figure 5a, while in Figure 5b the differences of the load angle $\Delta\delta$ of the G3 generator with separate excitation and self-excitation are given for the chosen durations of the short circuit.

With the aim to determine the behaviour of differ-



Slika 5 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim(NU) i samouzbudnim (SU) sustavom uzbude za slučaj kratkog spoja u čvorištu 6 pri trajanju kratkog spoja u mreži od $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 400$ ms

Figure 5 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation (SE) systems for the case of the short circuit in hub 6 for the duration of the short circuit in the network of $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 400$ ms



Slika 6 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim(NU) i samouzbudnim (SU) za slučaj kratkog spoja u čvorištu 6 uz isključeni vod 400 kV između čvorišta 1 i 7 pri trajanju kratkog spoja u mreži od $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 350$ ms

Figure 6 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation (SE) systems for the case of the short circuit in hub 6 with a switched-off 400 kV-line between hubs 1 and 7 for the duration of the short circuit in the network of $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 350$ ms

S ciljem da se odredi ponašanje različitih sustava uzbude u promijenjenim prilikama u prijenosnoj mreži isključen je vod 400 kV između čvorišta 1 i 7 i ponovljen je pokus kratkog spoja u čvorištu 6 (slika 5). Isključenje 400kV voda simulirano je povećanjem reaktancija Z_{1-6} (slika 2) na iznos od $Z_{1-6} = j \cdot 1\ 000$.

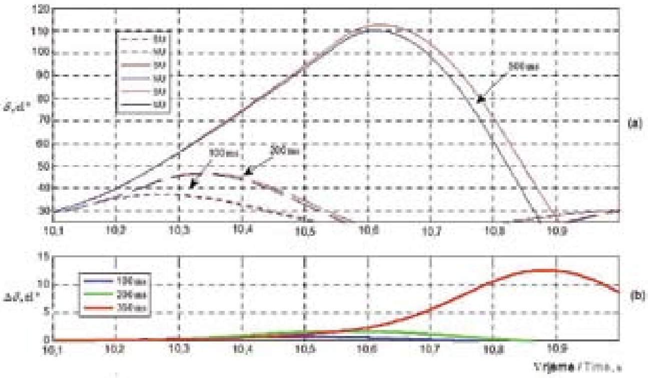
Proračun je napravljen za trajanje kratkog spoja od $T_k = 100$ ms, zatim je ponovljen za trajanje kratkog spoja od $T_k = 200$ ms i za trajanje kratkog spoja od $T_k = 350$ ms što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti. Razlike kutova opterećenja za sustav s nezavisnom uzbudom i samouzbudni sustav $\Delta\delta$ za generator G3 dane su na slici 6b.

Druga grupa proračuna provedena je u uvjetima pojave kratkog spoja u čvorištu 5 pri čemu je kratki spoj simuliran smanjivanjem reaktancije koja spaja čvorište 5 s referentnim čvorištem 0 (slika 2) s iznosa od $Z_{5-0} = j \cdot 10^3$ na $Z_{5-0} = j \cdot 10^{-3}$. Na slici 7a dani su usporedni odzivi kuta opterećenja sustava s nezavisnom uzbudom i samouzbudnog sustava, gdje su odabrana trajanja kratkog spoja u čvorištu 5 iznosila $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 500$ ms, što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti. Na slici 7b pokazana je razlika izračunatih kutova opterećenja $\Delta\delta$ za generator G3 kada je primijenjen sustav samouzbude i sustava s nezavisnom uzbudom.

ent excitation systems in different circumstances in the transmission network, the 400 kV line was switched off between nodes 1 and 7, and the test of the short circuit in node 6 was repeated (Figure 5). The switching-off of the 400 kV line was simulated by increasing the reactance Z_{1-6} (Figure 2) to the amount of $Z_{1-6} = j \cdot 1\ 000$.

The calculation was performed for the duration of the short circuit of $T_k = 100$ ms and then repeated for the duration of the short circuit of $T_k = 200$ ms, and for the duration of the short circuit of $T_k = 350$ ms which matches the critical time of duration of the short circuit according to the transitive stability criterion. Differences of load angles for the system with separate excitation and self-excitation system $\Delta\delta$ for the G3 generator are given in Figure 6b.

The second calculation group was performed in the conditions of occurrence of a short circuit in node 5 whereat the short circuit was simulated by reducing the reactance which connects node 5 to the reference node 0 (Figure 2) from the amount of $Z_{5-0} = j \cdot 10^3$ to $Z_{5-0} = j \cdot 10^{-3}$. Figure 7a provides the parallel responses of the load angles of the system with separate excitation and of the self-excitation system where the selected durations of the short circuit in node 5 amounted to $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 500$ ms which matches the critical time of duration of the short circuit according to the transitive stability criterion. Figure 7b shows the difference of calculated load angles $\Delta\delta$ for the G3 generator when the self-excitation system and the separate excitation systems are applied.



Slika 7 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim (NU) i samouzbudnim (SU) sustavom uzbude za slučaj kratkog spoja u čvorištu 5 pri trajanju kratkog spoja u mreži od $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 500$ ms

Figure 7 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation (SE) systems for the case of the short circuit in hub 5 for the duration of the short circuit in the network of $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 500$ ms

U nastavku je učinjen izračun za slučaj pojave kratkog spoja u čvorištu 5 u uvjetima koji nastaju pri trajnom ispadu mreže 400 kV i radu agregata na mreži 220 kV. Da bi se modeliralo opisano stanje potrebno je promijeniti vrijednosti reaktancija koje gledaju u čvoriše 6 tako da su, za slučaj trajnog ispada mreže 400 kV, reaktancije prema krutoj mreži povećane na vrijednosti: $Z_{1\text{–}7} = \mathrm{j}\cdot 0{,}5$, $Z_{2\text{–}7} = \mathrm{j}\cdot 0{,}5$i $Z_{3\text{–}7} = \mathrm{j}\cdot 0{,}5$.

Proračun je učinjen za različita vremena trajanja kratkog spoja u čvorištu 5: $T_k = 100$ ms, $T_k = 200$ ms i $T_k = 300$ ms što odgovara kritičnom vremenu trajanja kratkog spoja po kriteriju prijelazne stabilnosti, a dobiveni rezultati pokazani su na slici 8.

Postignute razlike kuta opterećenja $\Delta\delta$ generatora G3 za slučaj samouzbudnog sustava sustava s nezavisnom uzbudom i pokazane su na slici 8b.

4 ZAKLJUČAK

Razvijen je matematički model elektroenergetskog sustava s više sinkronih generatora u kojemu su generatori opisani nelinearnim matematičkim modelom. Istražen je utjecaj načina napajanja sustava uzbude na kutnu stabilnost generatora u uvjetima pojave kratkog spoja u mreži. S razvijenim postupkom provedeni su proračuni kuta opterećenja generatora u uvjetima pojave kratkog spoja na prijenosnoj mreži. Izračun je učinjen za različite konfiguracije prijenosne mreže i za različita vremena trajanja kratkog spoja. Rezultati simulacijskih proračuna pokazani su usporedbom kutova optereće-

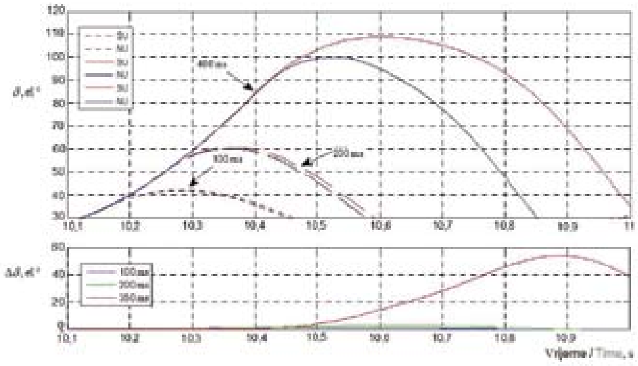
In the text below, calculation was made for the case of occurrence of a short circuit in node 5 in the conditions which appear at permanent outage of the 400 kV network and operation of the power generating set on the 220 kV network. In order to model the stated condition, it is necessary to change the values of the reactance which look at node 6 so that, in case of permanent outage of the 400 kV network, the reactance towards the infinite network are increased to the values: $Z_{1\text{–}7} = \mathrm{j}\cdot 0{,}5$, $Z_{2\text{–}7} = \mathrm{j}\cdot 0{,}5$ and $Z_{3\text{–}7} = \mathrm{j}\cdot 0{,}5$.

The calculation was performed for different durations of the short circuit in node 5: $T_k = 100$ ms, $T_k = 200$ ms and $T_k = 300$ ms which matches the critical time of duration of the short circuit according to the transitive stability criterion. The obtained results are shown in Figure 8.

The achieved differences of the load angles $\Delta\delta$ of the G3 generator for the case of the self-excitation system and the separate excitation system are shown in Figure 8b.

4 CONCLUSION

The paper elaborates on the mathematical model of the electric power system with several synchronous generators in which the generators are modelled by a non-linear mathematical model. The impact of the manner of supplying the excitation system on the angular stability of the generator was researched in the circumstances of occurrence of a short circuit in the network. By virtue of the derived procedure, load angle calculations were performed in the conditions of occurrence of a short circuit on the transmission network. The calculation was performed for different



Slika 8 — Usporedni prikaz odziva kuta opterećenja generatora G3 s nezavisnim (NU) i samouzbudom (SU) sustavom uzbude za slučaj kratkog spoja u čvorištu 5 pri trajnom ispada mreže 440 kV i radu agregata na mreži 220 kV pri trajanju kratkog spoja u mreži od T_k = 100 ms, T_k = 200 ms i T_k = 300 ms

Figure 8 — Parallel overview of the response of the load angle of the G3 generator with independent (IE) and self-excitation systems for the case of the short circuit in hub 5 at permanent outage of the 440 kV-network and operation of the power generating set on the 220 kV-network for the duration of the short circuit in the network of T_k = 100 ms, T_k = 200 ms and T_k = 300 ms.

nja generatora koji se postižu sa samouzbudnim sustavom i sustavom s nezavisnom uzbudom. Proračuni su provedeni za slučaj agregata u HE Dubrovniku.

Rezultati dobiveni proračunom pokazuju da agregati s nezavisnom uzbudom imaju bolje dinamičke karakteristike po kriteriju kutne stabilnosti jer pri identičnom poremećaju postižu manje kutove opterećenja iz čega se zaključuje da su otporniji na poremećaje u mreži. Razlike između kutova opterećenja kod promatranih sustava uzbude povećavaju se s povećanjem vremena trajanja kratkog spoja na mreži. Kao što se i očekivalo, proračuni su pokazali da dominantni utjecaj na pogonsku stabilnost generatora ima mjesto kvara u prijenosnoj mreži.

Postavljenim modelom moguće je istražiti utjecaj generatora s nezavisnom uzbudom na ukupnu kutnu stabilnost elektroenergetskog sustava. U razmatranje se može uzeti bitno veći dio elektroenergetskog sustava i provesti proračune za nekoliko karakterističnih pogonskih stanja sustava i pritom odrediti utjecaj koji bi odabrani generatori s nezavisnim sustavom uzbude imali na kutnu stabilnost elektroenergetskog sustava.

Razvijeni postupak omogućuje relativno jednostavno proširenje na način da se poveća broj čvorišta, grana mreže i generatora.

transmission network configurations and for different durations of the short circuit. The results of calculations are shown by comparing the generator load angles which are achieved by the self-excitation system and the separate excitation system. The calculations were performed for the case of the power generating set at the Dubrovnik hydroelectric power plant.

The results obtained by calculation show that the independent-excitation power generating sets have better dynamic characteristics according to the angular stability criterion because at an identical disruption they achieve smaller load angles. This gives rise to the conclusion that these are more resistant to the disruptions in the network. The differences between the load angles at the observed excitation systems increase with the increase of the time of duration of the short circuit in the network. As expected, the calculations showed that the major impact factor on the generator's drive stability is the place of the failure in the transmission network.

The set model provides for the research of the impact of the self-excitation generator on the total angular stability of the electric power system. The major part of the electric power system can be included in the observation and calculations can be performed for several characteristic drive conditions of the system, and thereat the impact can be defined which the selected independent-excitation system generators would have on the angular stability of the electric power system.

The derived procedure provides for a relatively simple expansion so as to increase the number of hubs, network branches and generators.

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