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Igor Erceg, Gorislav Erceg, Damir Sumina

Development and Implementation of Control Algorithms for Synchronous Generator

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Original scientific paper

This paper proposes a DSP based simulator for development and implementation of control algorithms. The simulator is used to control a synchronous aggregate model in real time. The simulator consists of a PC (on which a synchronous generator connected to AC network is simulated) connected through a communication channel to a DSP (on which the control algorithm is implemented). The simulator makes implementation of a control algorithm faster and easier. It also enables verification of a control algorithm in real time. Simulation results show that there are no significant differences between non-real time simulations (on a PC) and real time simulations (on a DSP based simulator). This paper also presents design and implementation of a nonlinear control algorithm for excitation control system based on the Lyapunov's direct method. Both conventional excitation control algorithm and proposed nonlinear excitation control algorithm were implemented and tested on the real time simulator. The obtained simulation results show that proposed nonlinear excitation control algorithm better damps electromechanical oscillations than conventional excitation control algorithm.

Key words: Dynamic simulator, Excitation control, Real time system, Synchronous generator

Razvoj i implementacija upravljačkih algoritama za sinkroni generator. U radu je prezentirana upotreba simulatora za rad u stvarnom vremenu za razvoj i implementaciju upravljačkih algoritama. Simulator je korišten za upravljanje modelom sinkronog agregata u realnom vremenu. Simulator se sastoji od osobnog računala (na kojem se simulira model generatora spojen na elektroenergetski sustav) koje je preko komunikacijskog kanala spojen na DSP (na koji je implenetiran upravljački algoritam). Simulator omogućuje bržu i jednostavniju implementaciju upravljačkog algoritma. Isto tako omogućuje verifikaciju upravljačkog algoritma u realnom vremenu. Isto tako, u ovom radu dana je izvedba i implementacija nelinearnog algoritma upravljanja uzbudom zasnovana na direktnoj teoriji Ljapunova. I klasičan i predloženi nelinearni algoritam upravljanja uzbudom su implementirani i testirani na simulatoru za rad u stvarnom vremenu. Rezultati simulacije pokazuju da sustav s predloženim nelinearnim algoritmom upravljanja uzbudom bolje prigušuje elektromehaičke oscilacije u odnosu na sustav s klasičnim algoritmom upravljanja uzbudom.

Ključne riječi: dinamički simulator, regulacija uzbude generatora, sustavi za rad u stvarnom vremenu, sinkroni generator

1 INTRODUCTION

Testing a controller for complex control systems demands a real control system or an adequate laboratory model. After engineering the necessary electronic circuits, simulating and implementing the control algorithm, controller operation should be verified on a real system. With complex systems, such as the power system, engineering an adequate laboratory model is difficult and expensive, and the real operating systems are rarely put to a stop so as to examine the operation of a controller. It is desirable, for technical and economic reasons, to have a dynamic simulator which would simulate the physical behaviors of real complex systems [1–3].

Control algorithms implementation and their testing on the dynamic simulator for a synchronous generator excitation control system are presented in this paper. A synchronous generator is simulated in real time using a Matlab/Simulink program package. Control algorithms were implemented on a TMS320F28335 digital signal processor (DSP) of Texas Instruments. The dynamic simulator (Fig. 1) consists of a PC (simulating a synchronous generator) connected by a communication channel (through a USB port) to a DSP (on which the control algorithm has been implemented).

The data exchange between PC and DSP is carried out by a JTAG (Join Test Action Group) emulator through the Real Time Data eXchange interface (RTDX). This kind

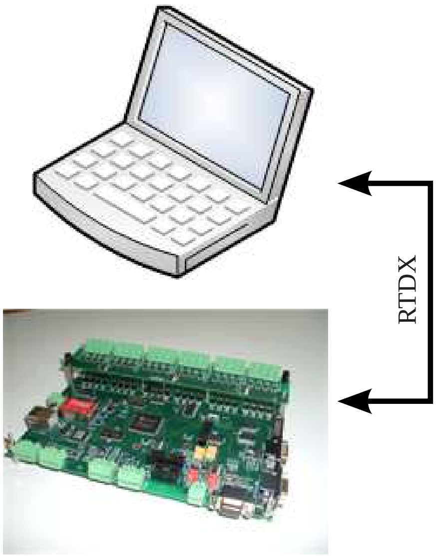

Fig. 1: DSP based platform

of dynamic simulator for implementing and testing of a controller is less technically and economically demanding than if the testing was conducted on an adequate laboratory model or on a real system. With an adequate mathematical and simulation model different control systems can also be simulated on the dynamic simulator. Also, input/output signals of a real system can be connected to the dynamic simulator to test the operation of an implemented controller (processor/hardware in the loop simulations). The dynamic simulator contains commercial electronic components that are easily accessible and economically acceptable.

This paper presents design and implementation of a conventional and nonlinear control algorithm based on the Lyapunov's direct method for synchronous generator excitation control system. Simulation model of a synchronous generator connected to infinite bus through a step-up transformer and transmission lines (reactance of transmission line is 0.2; Fig. 2) was used for testing excitation control algorithms.

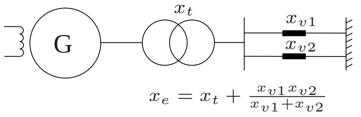

Fig. 2: Synchronous generator connection to the AC network

Fig. 3 shows conventional generator excitation control system structure. Generator excitation control system consists of a proportional field current controller and a PI voltage controller which is super-ordinate to it [4, 5]. The control system input signals are two measured phase currents, two line voltages, generator field current, rotor speed and load angle, while the system output signal is a PWM signal for an AD/DC converter. The power system stabilizer (PSS) output signal is an input signal in a summation point before voltage controller in the excitation control system. The structure of PSS type PSS1A is shown in Fig. 4 [4]. Commonly used input signals of PSS are rotor speed, active power or terminal frequency [4]. In this paper active power is used as an input of the PSS. PSS1A stabilizer parameters, given in AppendixA.4, were experimentally determined using the phase compensation technique with a generator voltage of 1.0 p.u. and an active power of 1.0 p.u. [6].

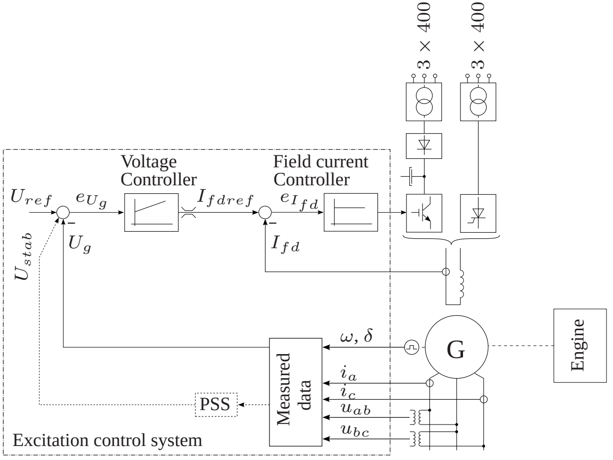

Fig. 3: Conventional generator excitation control system

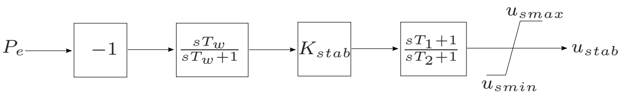

Fig. 4: Structure of IEEE-type PSS1A stabilizer

The paper is organized as follows. Description of the single machine infinite bus model is given in Section 2. Simulation model of a conventional excitation control system is described in Section 3. Design and implementation of a conventional excitation controller is given in Section 4. Design of a nonlinear excitation control algorithm is given in Section 5. Simulation results are given in Section 6. Concluding remarks are given in Section 7.

2 SIMULATION MODEL OF THE SYNCHRONOUS GENERATOR

Before implementing and testing a control algorithm on a real system, it is necessary to make an adequate mathematical and simulation model of a real system. The mathematical two axes model of a symmetrically loaded synchronous generator (machine) is described by the following differential equations [7]:

$$\begin{aligned}
U_d &= -\,I_d R_s - \omega\psi_q + \frac{\mathrm{d}\,\psi_d}{\omega_s\,\mathrm{d}\,t} && \text{[p.u.]}\\
U_q &= -\,I_q R_s + \omega\psi_d + \frac{\mathrm{d}\,\psi_q}{\omega_s\,\mathrm{d}\,t} && \text{[p.u.]}\\
U_0 &= -\,I_0 R_s + \frac{\mathrm{d}\,\psi_0}{\omega_s\,\mathrm{d}\,t} && \text{[p.u.]}\\
U_{fd} &= I_{fd} R_{fd} + \frac{\mathrm{d}\,\psi_{fd}}{\omega_s\,\mathrm{d}\,t} && \text{[p.u.]}\\
0 &= I_{kd} R_{kd} + \frac{\mathrm{d}\,\psi_{kd}}{\omega_s\,\mathrm{d}\,t} && \text{[p.u.]}\\
0 &= I_{kq} R_{kq} + \frac{\mathrm{d}\,\psi_{kq}}{\omega_s\,\mathrm{d}\,t} && \text{[p.u.]}
\end{aligned} \tag{1}$$

Flux linkage/current relationships are defined by:

$$\begin{aligned}
\psi_d &= -X_d I_d + X_{md} I_{fd} + X_{md} I_{kd}\\
\psi_q &= -X_q I_q + X_{mq} I_{kq}\\
\psi_{fd} &= -X_{md} I_d + X_{fd} I_{fd} + X_{md} I_{kd}\\
\psi_{kd} &= -X_{md} I_d + X_{md} I_{fd} + X_{kd} I_{kd}\\
\psi_{kq} &= -X_{mq} I_q + X_{kq} I_{kq}\\
\psi_0 &= -X_{ls} I_0
\end{aligned} \tag{2}$$

The aggregate motion equations are:

$$T_M \frac{\mathrm{d}\,\omega}{\mathrm{d}\,t} = M_m - M_e \tag{3}$$

$$\frac{\mathrm{d}\,\delta}{\mathrm{d}\,t} = (\omega - 1)\,\omega_s \tag{4}$$

The electromagnetic torque of the generator is determined by equation:

$$M_e = (\psi_d I_q - \psi_q I_d) \tag{5}$$

Connection between the synchronous generator and AC network is determined by the following equations:

$$U_d = U_{sd} + \frac{X_e}{\omega_s}\frac{\mathrm{d}\,I_d}{\mathrm{d}\,t} - \omega I_q X_e + I_d R_e \tag{6}$$

$$U_q = U_{sq} + \frac{X_e}{\omega_s}\frac{\mathrm{d}\,I_q}{\mathrm{d}\,t} + \omega I_d X_e + I_q R_e \tag{7}$$

$$U_{sd} = U_s \sin\delta \tag{8}$$

$$U_{sq} = U_s \cos\delta \tag{9}$$

where equivalent AC network voltage, transmission line reactance and resistance are considered constant ($U_s = 1$ p.u.).

Simulation model of a synchronous generator, with a conventional excitation control system, connected to a power system was simulated in Matlab/Simulink (Fig. 5). Simulation model includes a proportionally integral (PI) voltage controller and a proportional (P) generator field current controller. After performing simulations on a designed model it is necessary to implement the control algorithms no an existing control excitation system. Nowadays, digital signal processors (DSP) are often used as control units in an excitation control system of a synchronous generator. DSPs are used due to the large quantities of data that need to be processed in a short amount of time. Until recently, a DSP could only be programmed in a high-level languages (C/C++, Java, etc.) or in an assembler. This demands additional knowledge of DSP programming.

Controller operation must be verified after implementation of the control algorithm on a DSP. A laboratory model of a generator excitation control system is complex and may not be profitable. Also, it is rarely possible to perform excitation control system tests on the real power plant, because it demands that the power plant operation be stopped.

3 SIMULATION MODEL OF AN EXCITATION CONTROL SYSTEM

The simulation model of a synchronous generator, with a conventional excitation control system, connected to a power system (Fig. 5) describes physical behavior of the system well. Various excitation control algorithms can be tested on this model. The given simulation model does not operate in real time and the limits of actuating units within the control system have been ignored, such as processor type (32-bit, 16-bit, fixed-point or floating-point), data processing speed, date transfer speed, signal filtration in cases of analog-digital conversion, etc. Besides, this model is not suitable for the direct implementation of the control algorithm on a DSP, because it is simulated using the variable-step method (ode45; Dormand-Prince). Also, it's not possible to know the exact state of the simulated physical variables in an exact moment.

The PI voltage controller and the P field current controller from the synchronous simulation model must be realized in the discrete domain (Fig. 6), so the algorithm can be implemented on a DSP. The voltage reference signal, as well as the measured voltage and measured field current signals, have to be discrete. This is done using the Zero-Order Hold function.

4 USING DSP PLATFORM FOR IMPLEMENTING AND TASTING OF ALGORITHMS

The dynamic simulator works with a 32-bit floating-point TMS320F28335 DSP. Fig. 7 shows the synchronous generator control algorithm implemented on the DSP based dynamic simulator. Control algorithm is block-programmed, translated to a high-level language (C/C++)

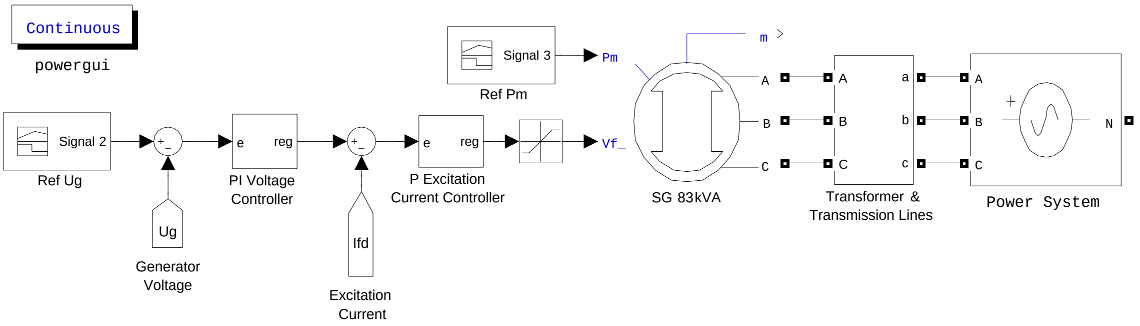

Fig. 5: Simulation model of synchronous generator excitation control system

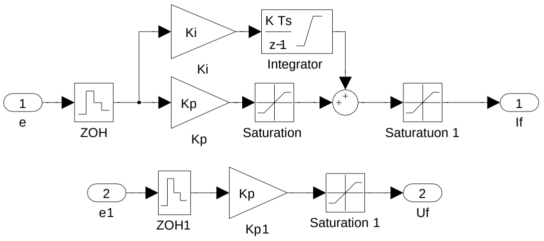

Fig. 6: PI voltage controller and P field current controller in discrete form

and downloaded on a DSP using Matlab/Simulink (with TC2 Target Support Package) [8–11].

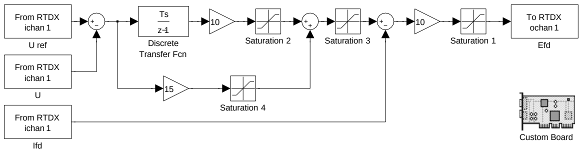

Fig. 7: Synchronous generator excitation control algorithm on a DSP based dynamic simulator

4.1 Testing of conventional algorithm

The generator excitation control system operation was tested for the cases of voltage reference step change and for the three-phase short circuit disturbance on one of the transmission lines (Fig. 2). Fig. 8 show the generator responses for the case of a three-phase short circuit which happened at 0.3 seconds and lasted 100 ms, and for voltage reference step change from the initial value of 1 p.u. to the value of 0.8 p.u. Comparison of the simulation results between non-real time simulation (performed only on a PC) and real time simulation (performed on a DSP based dynamic simulator) show no significant differences. The real time simulation model controlled by the DSP dynamic simulator has an 0.8 ms delay compared to the non-real time simulation model simulated on a PC (Fig. 9). The simulator delay is caused because of the data exchange delay between the DSP and PC.

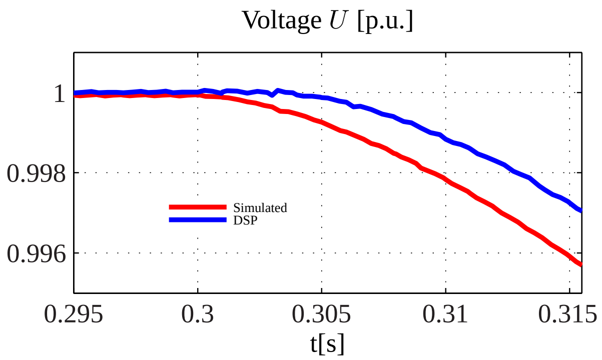

Fig. 9: Time delay between simulation performed on a PC and on a DSP based dynamic simulator

5 DESIGN OF THE NONLINEAR ALGORITHM

The parameters and characteristics of a conventional voltage controller are determined based on a linearized synchronous generator model operating at a specific operating point. This kind of a controller is not robust to generator operating point changes and to system structure changes (transmission line fall outs, short circuits on a transmission lines, etc.). The power system keeps making bigger demands to the power units and thereby to the generator excitation control system. This imposes the need to explore other types of synchronous generator excitation system control algorithms.

The mathematical two axes model of a symmetrically loaded synchronous generator (1) is highly nonlinear and complex. Such a complex model is very difficult to deal with, in the controller design and implementation, unless some simplifications are made [12]. The simplified third order mathematical model of a hydrogenerator (resistances of the stator coils and transient processes in damping coils

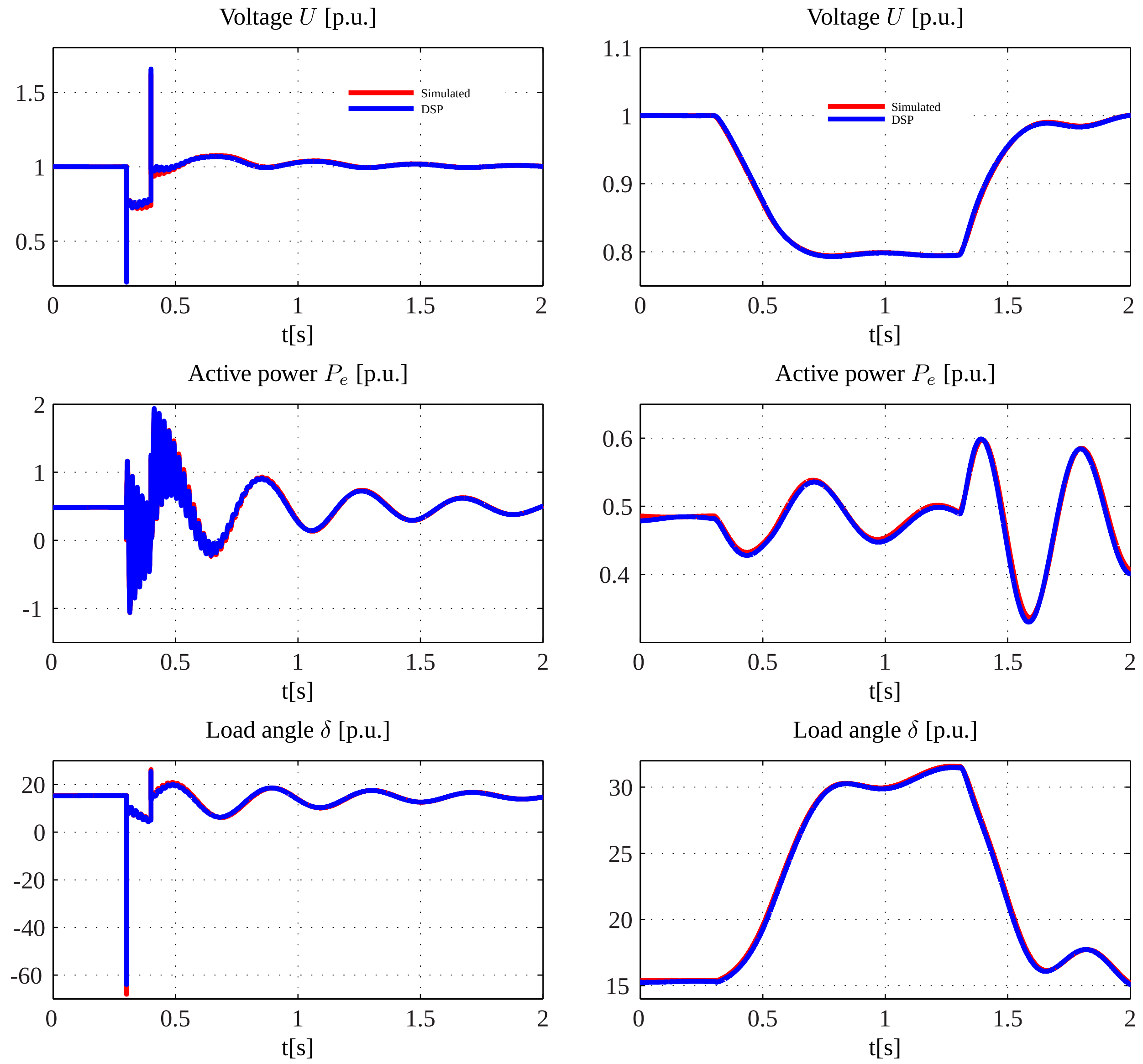

Fig. 8: Simulation results for a three-phase short circuit (left) and for a voltage reference step change (right) using a non-real time simulation (performed on a PC - red) and a real time simulation (performed on a DSP based dynamic simulator - blue)

are neglected), which is connected to an AC network via step-up transformer and transmission lines (Fig. 2), was used to develop the nonlinear excitation control algorithm based on the Lyapunov's direct method [13–15]. This kind of a simplification assumes very small speed deviation ($\Delta\omega \approx 0$). So, instead using mechanical and electrical torque, motion equation (5) can be written using mechanical and electrical power (11).Vector diagram of a hydrogenerator connected to AC network is presented on the Fig. 10.

The simplified third order mathematical model of synchronous generator connected to AC network is given by [14, 15]:

$$\frac{d\delta}{dt} = \omega_s \Delta\omega \tag{10}$$

$$T_m \frac{d\Delta\omega}{dt} = P_m - P_e \tag{11}$$

$$T'_{d0} \frac{dE'_q}{dt} = E_f - I_{fd} X_{md} \tag{12}$$

where δ [rad] is the load angle, $\Delta\omega$ [p.u.] is speed deviation and E'_q [p.u.] is the q axis component of the voltage

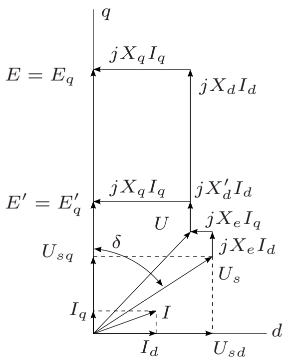

Fig. 10: Vector diagram of hydro generator connected to AC network

behind transient reactacne X'_d. P_e [p.u.] denotes generator active power which comes to:

$$P_e = \frac{E'_qU_s}{X'_d + X_e}\sin\delta + \frac{U_s^2}{2}\frac{X'_d - X_q}{(X_e + X'_d)(X_e + X_q)}\sin 2\delta$$

Lyapunov's direct method is an effective tool for the stability of nonlinear systems. For autonomous differentiable systems, Lyapunov function is a convinient tool to analyze the asymptotic stability properties if the equilibrium points [16]. One notably successful use of the Lyapunov methodology is its generalization to control system design, known as the control Lyapunov function (CLF). The existence of the CLF is also a necessity and sufficient condition for the stability of nonlinear systems with inputs. By using a CLF, many control algorithms can be calculated which globally asymptotically stabilize the system. The main drawback of the CLF concept, as a design tool, is that there are no systematic ways of finding a control Lyapunov function for the general nonlinear systems [16–21].

Further on, by using control Lyapunov function a nonlinear excitation control algorithm was developed.

Assuming Lyapunov's function:

$$V = \frac{1}{2}e^2 > 0 \qquad \forall e \neq 0 \tag{13}$$

$$e = U - U_{ref} \tag{14}$$

where e is the error between the terminal voltage value and voltage reference value.

Adding (14) into (13) and differentiating the equation (13) leads to:

$$\frac{dV}{dt} = (U - U_{ref}) \cdot \frac{dU}{dt} = e \cdot \frac{dU}{dt} \tag{15}$$

Substitution of generator voltage $U = \sqrt{U_d^2 + U_q^2}$ in the equation (15) gives:

$$\frac{dV}{dt} = \frac{e}{U}(U_d\frac{dU_d}{dt} + U_q\frac{dU_q}{dt}) \tag{16}$$

From the generator vector diagram (Fig. 10), voltages U_d i U_q can be calculated as follows:

$$U_d = U_s\sin(\delta)\frac{X_q}{X_e + X_q} \tag{17}$$

$$U_q = E'_q\frac{X_e}{X'_d + X_e} + U_s\cos(\delta)\frac{X'_d}{X'_d + X_e} \tag{18}$$

respectively:

$$\frac{dU_d}{dt} = U_s\frac{X_q}{X_e + X_q}\cos(\delta)\omega_s\Delta\omega \tag{19}$$

$$\begin{aligned}\frac{dU_q}{dt} &= \frac{1}{T'_{d0}}(E_{fd} - I_{fd}X_{md})\frac{X_e}{X'_d + X_e} - \\ &- U_s\frac{X'_d}{X'_d + X_e}\sin(\delta)\omega_s\Delta\omega\end{aligned} \tag{20}$$

Adding the equations (19) and (20) to the equation (15) leads to:

$$\begin{aligned}\frac{dV}{dt} =& \frac{e}{U}\Bigg[U_d\frac{X_q}{X_e + X_q}U_s\cos(\delta)\omega_s\Delta\omega + \\ &+ U_q\frac{1}{T'_{d0}}E_{fd}\frac{X_e}{X'_d + X_e} + U_q\left(-\frac{1}{T'_{d0}}I_{fd}\right. \\ &\left.X_{md}\frac{X_e}{X'_d + X_e} - \frac{X'_d}{X'_d + X_e}U_s\sin(\delta)\omega_s\Delta\omega\right)\Bigg]\end{aligned} \tag{21}$$

Let the control rule have the following form:

$$\begin{aligned}E_{fd} =& - T'_{d0}\frac{X'_d + X_e}{X_e}\frac{1}{U_q}\,[K_1e + \\ &+ K_2U_d\frac{X_q}{X_e + X_q}U_s\cos(\delta)\omega_s\Delta\omega + \\ &+ K_3U_q\left(-\frac{1}{T'_{d0}}I_{fd}X_{md}\frac{X_e}{X'_d + X_e} - \right. \\ &\left. - \frac{X'_d}{X'_d + X_e}U_s\sin(\delta)\omega_s\Delta\omega\right)\Bigg]\end{aligned} \tag{22}$$

where K_1, K_2 and K_3 are parameters which force Lyapunov's function derivation to be negative at every generator operating point.

Implementing the control rule (22) into the equation (21) leads to:

$$\begin{aligned}\frac{dV}{dt} =& - K_1\frac{e^2}{U} + \frac{e}{U}\left[U_d\frac{X_q}{X_e + X_q}U_s\cos(\delta)\right. \\ &\omega_s\Delta\omega(1 - K_2) + U_qY(1 - K_3)]\end{aligned} \tag{23}$$

where:

$$Y = -\frac{1}{T'_{d0}}I_{fd}X_{md}\frac{X_e}{X'_d + X_e} - \frac{X'_d}{X'_d + X_e}U_s\sin(\delta)\omega_s\Delta\omega$$

In order for the system to be stable according to Lyapunov, the following must be valid at every generator operating point: $\frac{dV}{dt} \leq 0$. It is obvious from the first part of equation (23) that $-K_1 \frac{e^2}{U} < 0$ is valid for any $K_1 > 0$ (generator voltage $U > 0$ at every generator operating point), whereas the second part depends on $\Delta\omega$, δ, U_d and U_q. If the derivation of Lypunov's function (23) is to be negative, the following inequality must hold:

$$
\begin{aligned}
&-K_1 \frac{e^2}{U} + \frac{e}{U} \left[U_d \frac{X_q}{X_e + X_q} U_s \cos(\delta) \right. \\
&\left. \omega_s \Delta\omega (1 - K_2) + U_q Y (1 - K_3) \right] < 0
\end{aligned}
$$

During smaller disturbances synchronous generator speed is approximately equal to synchronous speed, i.e. $\Delta\omega \approx 0$, and with the selected $K_3 = 1$ this means:

$$
\frac{dV}{dt} \approx -K_1 \frac{e^2}{U} < 0
$$

Although it has been assumed that $\Delta\omega \approx 0$, the simulation results stated in the following section show that the proposed nonlinear excitation control algorithm gives satisfactory results even in cases of larger disturbances. The nonlinear excitation control algorithm has three adjustable parameters (K_1, K_2 and K_3). The adjustment has been made by identifying the optimal generator's active power response to the voltage reference change from 1 p.u. to 0.95 p.u. with active power 1 p.u. The performance of the proposed nonlinear control algorithm has been evaluated by te discrete time quadratic performance index J expressed as:

$$
J = \sum_{k=0}^{n} \left(\Delta P\left(k\right) k \Delta T \right)^2
$$

where ΔP is the generator active deviation, k is the sample number from 0 to n and ΔT is the sampling time. The parameters of the proposed nonlinear control algorithm are given in Appendix A.3. The nonlinear excitation control algorithm not only keeps generator terminal voltage equal to the reference voltage, but also damps generator electromechanical oscillations.

6 COMPARISON OF THE CONVENTIONAL AND NONLINEAR CONTROL ALGORITHM

Real time DSP based dynamic simulator was used for evaluation of the proposed nonlinear excitation control algorithm. Also, conventional excitation control algorithms (with and without PSS) were simulated using the real time DSP based dynamic simulator. The simulation results were used for the comparison of the conventional (with and without PSS) and proposed nonlinear excitation control system (Fig. 11, Fig. 12 and Fig. 13). Simulation results for mechanical power change from 0.5 to 0.8 and again to 0.5 p.u. at generator voltage 0.9 p.u. are shown in Fig. 11. Fig. 12 shows simulation results for a generator voltage reference change from the initial value of 1 p.u. to the value of 0.8 p.u. and back to 1 p.u. at generator mechanical power at 0.8 p.u. Fig. 13 shows simulation results for a three-phase short circuit (that lasted 100ms) on one of the transmission lines. Presented results show that the proposed nonlinear excitation control algorithm achieves better performance than conventional excitation control algorithms.

7 CONCLUSION

Real time DSP based dynamic simulator enables faster processes of engineering, implementing and verifying control algorithms not only for excitation control system of a synchronous generator, but also for other systems able of having an adequate mathematical and simulation model. Programming of control algorithms is block based and a program code is automatically generated, translated and downloaded on the DSP using Matlab/Simulink. The simulator verifies control algorithm by a simulation in real time, where the simulated model of the controlled system is performed on a PC. Comparison of the simulation results between non-real time simulation (performed only on a PC) and real time simulation (performed on a DSP based dynamic simulator) show no significant differences. The real time simulation model controlled by the DSP dynamic simulator has an 0.8 ms delay compared to the non-real time simulation model simulated on a PC.

Also, design and implementation of a nonlinear control algorithm for excitation control system based on the Lyapunov's direct method is given. Both conventional excitation control algorithms and proposed nonlinear excitation control algorithm were implemented and tested on the real time simulator. Presented results show that the proposed nonlinear excitation control algorithm not only keeps generator terminal voltage equal to the reference voltage, but also better damps generator electromechanical oscillations than conventional excitation control algorithms.

Extensions to the work presented in this paper are planned in several directions. Implementation and verification of a proposed nonlinear excitation control algorithm on an adequate synchronous generator laboratory model. Further investigation of designing a nonlinear excitation algorithm by using a more detailed mathematical model of a synchronous generator and different Lyapunov function candidates.

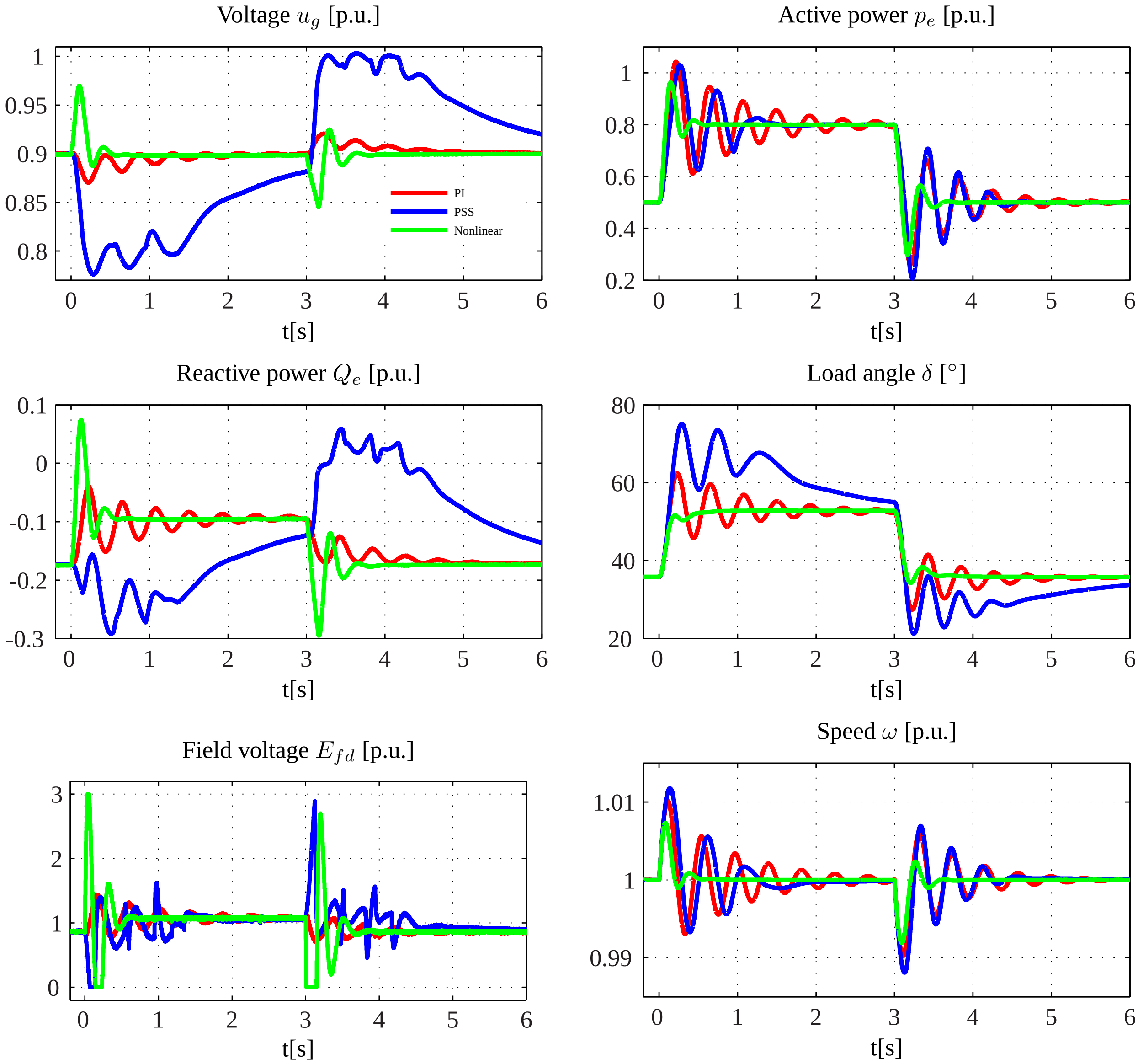

Fig. 11: Simulation results for a mechanical power gate change for the conventional excitation system without PSS (red), for the conventional excitation system with PSS (blue) and for the proposed nonlinear excitation system (green)

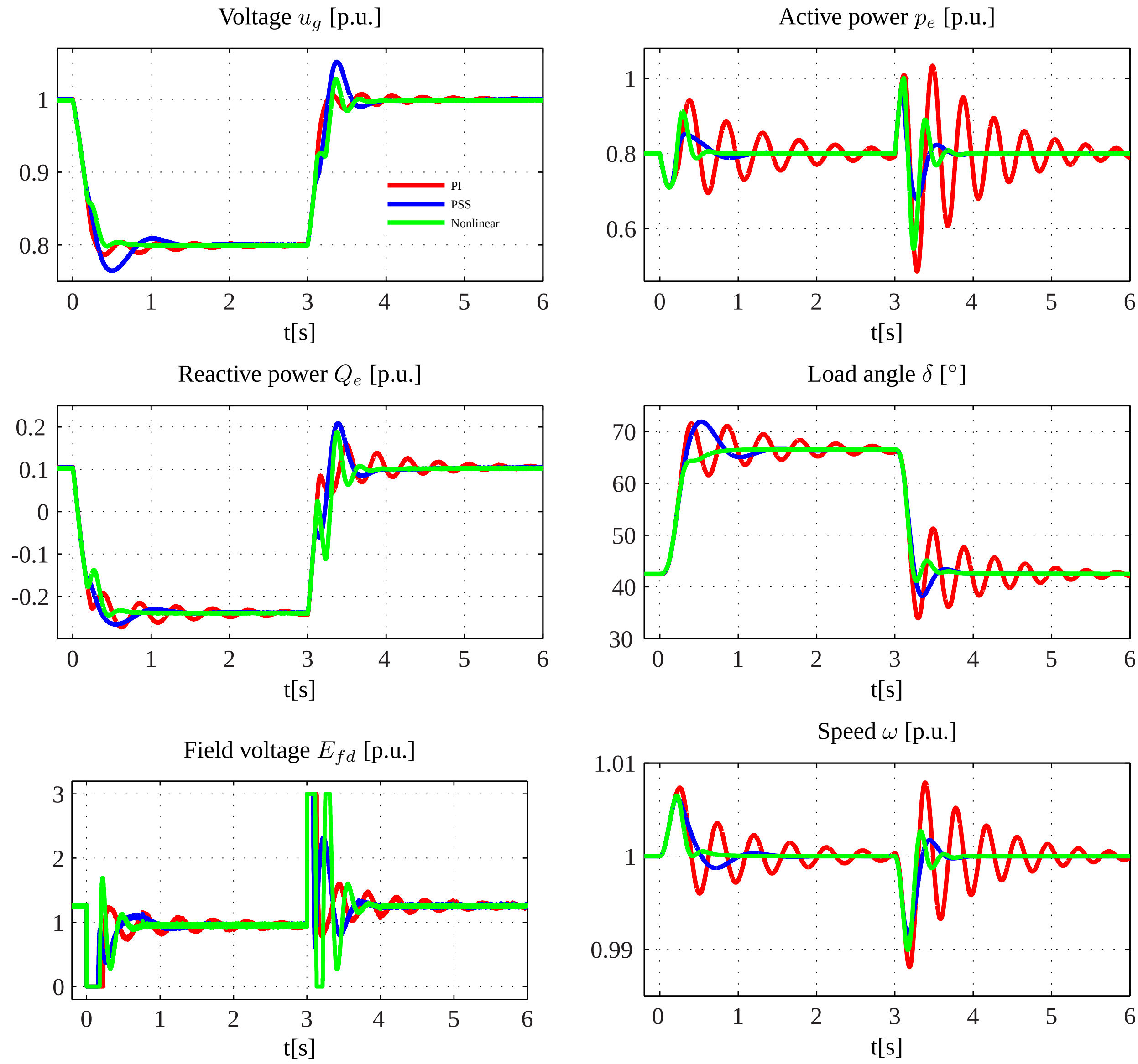

Fig. 12: Simulation results for a voltage reference gate change for the conventional excitation system without PSS (red), for the conventional excitation system with PSS (blue) and for the proposed nonlinear excitation system (green)

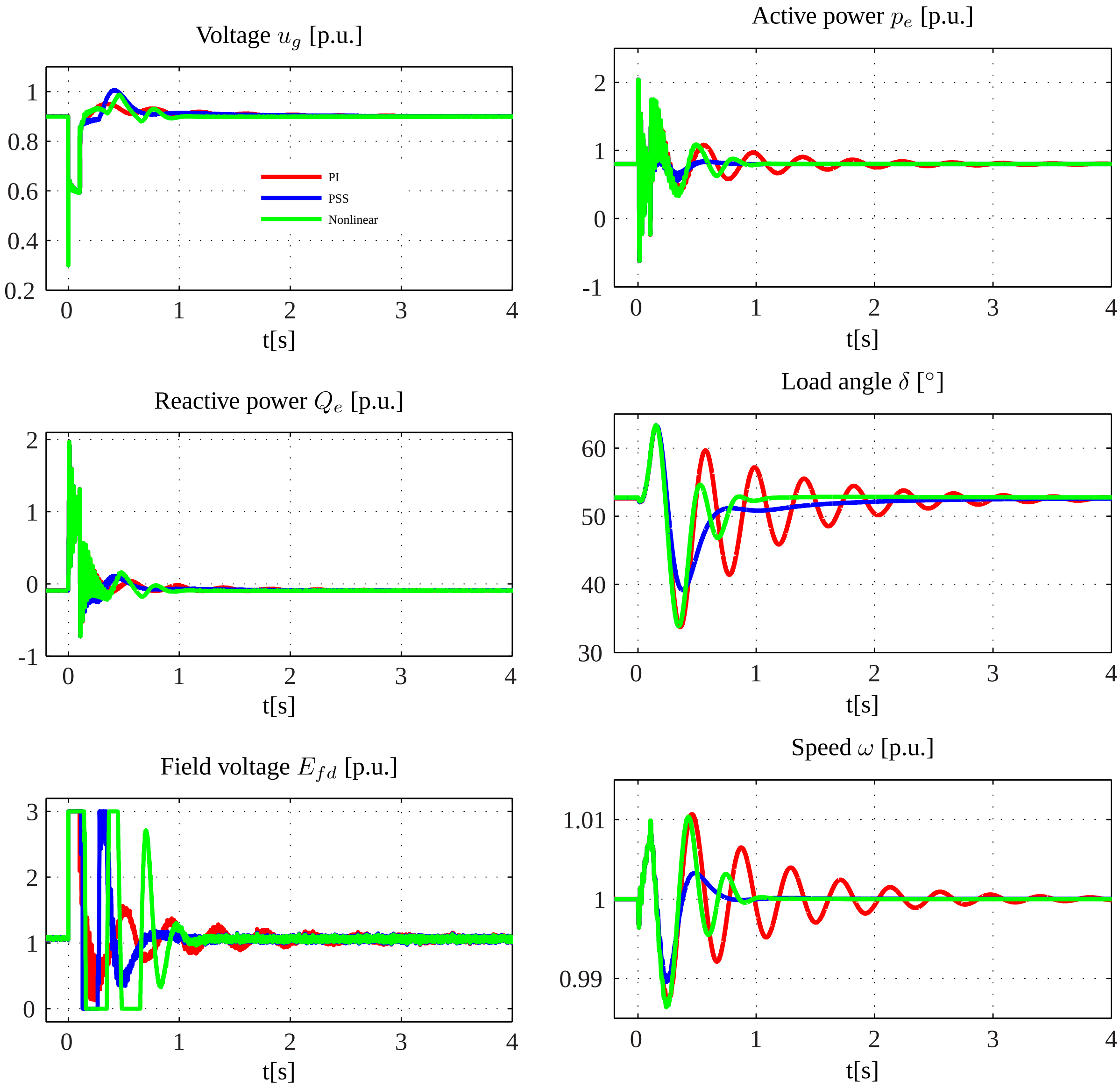

Fig. 13: Simulation results for a three-phase short circuit disturbance on one of the transmission lines for the conventional excitation system without PSS (red), for the conventional excitation system with PSS (blue) and for the proposed nonlinear excitation system (green)

APPENDIX A

A.1 List of symbols

The list of symbols is given in table 1.

Table 1: List of symbols

U_d	d-axis component of the generator terminal voltage ($p.u.$)
U_q	q-axis component of the generator terminal voltage ($p.u.$)
U_{fd}	excitation voltage ($p.u.$)
U_s	infinite busbar voltage ($p.u.$)
U_{sd}	d-axis component of the infinite busbar voltage ($p.u.$)
U_{sq}	q-axis component of the infinite busbar voltage ($p.u.$)
I_d	d-axis component of the generator stator current ($p.u.$)
I_q	q-axis component of the generator stator current ($p.u.$)
I_{fd}	field current ($p.u.$)
I_{kd}	d-axis field damper current ($p.u.$)
I_{kq}	q-axis field damper current ($p.u.$)
R_s	generator stator resistance ($p.u.$)
R_{fd}	excitation resistance ($p.u.$)
R_{kd}	d-axis damper resistance ($p.u.$)
R_{kq}	q-axis damper resistance ($p.u.$)
ω	generator rotor speed ($p.u.$)
ω_s	synchronous speed (rad/s)
Ψ_d	d-axis flux linkage ($p.u.$)
Ψ_q	q-axis flux linkage ($p.u.$)
Ψ_{fd}	field flux linkage ($p.u.$)
Ψ_{kd}	d-axis field damper flux linkage ($p.u.$)
Ψ_{kq}	q-axis field damper flux linkage ($p.u.$)
X_d	d-axis synchronous reactance ($p.u.$)
X_q	q-axis synchronous reactance ($p.u.$)
X_{fd}	field reactance ($p.u.$)
X_{kd}	d-axis damper reactance ($p.u.$)
X_{kq}	q-axis damper reactance ($p.u.$)
X'_d	d-axis transient reactance ($p.u.$)
X_{md}	d-axis armature reaction reactance ($p.u.$)
X_{mq}	q-axis armature reaction reactance ($p.u.$)
X_e	transformer and transmission line reactance ($p.u.$)
R_e	transformer and transmission line resistance ($p.u.$)
δ	rotor angle (rad)
M_m	mechanical torque ($p.u.$)
M_e	electromagnetic torque ($p.u.$)
P_m	mechanical power ($p.u.$)
P_e	active power ($p.u.$)
Q_e	reactive power ($p.u.$)
T_M	mechanical time constant (s)
E'_q	q-axis component of transient EMF ($p.u.$)
E_{fd}	field voltage ($p.u.$)

A.2 Generator parameters

The synchronous generators rated parameters are given in table 2.

Table 2: The synchronous generators rated parameters

Voltage	400 V
Current	120 A
Power	83 kVA
Frequency	50 Hz
Speed	600 r/min
Power factor	0.8
Excitation voltage	100 V
Excitation current	11.8 A

A.3 Controllers parameters

The controllers parameters are given in table 3.

Table 3: The controllers parameters

Voltage controller	
K_p	10
K_i	15
Excitation current controller	
K_p	10
Nonlinear controller	
K_1	50
K_2	-7
K_3	1

A.4 PSS parameters

The power system stabilizer parameters are given in table 4.

Table 4: The power system stabilizer parameters

T_w	1 s
K_{stab}	2
T_1	0.01 s
T_2	0.1 s
u_{smax}	0.1
u_{smin}	-0.1

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Igor Erceg received his Ph.D.E.E. in 2010 and B.S.E.E. in 2004 at the Faculty of Electrical Engineering and Computing, University of Zagreb. From 2004 he has been working as an assistant at the Faculty of Electrical Engineering and Computing (Department of electrical machines, drives and automation). His fields of interests are power system stability analyses, power system operation and control and excitation control of synchronous generators. He authored many papers published in journals and presented at national and international conferences.

Gorislav Erceg received his BSEE, MSEE and PhD degrees from University of Zagreb, Faculty of Electrical Engineering and Computing in 1964, 1975 and 1996, respectively. In 1966 at the Faculty of Electrical Engineering and Computing, Zagreb, Croatia he started as an assistant of Fundamentals of Electrical Engineering. He works today at Faculty of Electrical Engineering (Department of Industrial Plants and Automation), Osijek, Croatia. Also, he is a project leader of several industrial and government projects. He authored numerous papers published in journals and presented at national and international conferences.

Damir Sumina received his Ph.D.E.E. in 2009, M.S.E.E. in 2005 and B.S.E.E. in 2001 at the University of Zagreb, Croatia. From 2001 he has been working as assistant at the Faculty of Electrical Engineering and Computing (Department of electrical machines, drives and automation). His fields of interests are power system stability analyses, power system operation and control and excitation control of synchronous generators. He has been author of many papers published in journals and presented at national and international conferences.

AUTHORS’ ADDRESSES
Igor Erceg, Ph.D.
Prof. Gorislav Erceg, Ph.D.
Damir Sumina, Ph.D.
Department of Electric Machines, Drives and Automation,
Faculty of Electrical Engineering and Computing,
University of Zagreb,
Unska 3, HR-10000 Zagreb, Croatia
email: igor.erceg@fer.hr, gorislav.erceg@fer.hr,
damir.sumina@fer.hr

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