DSP based simulator for excitation control of synchronous generator

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Abstract: - This paper proposes a DSP based simulator for the implementing and testing control algorithms. The simulator is used to control a synchronous power plant model in real time. The simulator consists of a PC, on which the synchronous generator connected to AC network is simulated, connected through a communication channel to a DSP into which the control algorithm has been implemented. The simulator enables verification of the control algorithm on a simulation model in real time. In real time the simulator enables faster processes of engineering, implementing and verifying control algorithms not only for the voltage control system of a synchronous generator, but also for other systems able of having mathematical and simulation models. This paper shows a comparison in the case when both the system model and the control structure are simulated and for a case when the model is simulated on a computer and the control structure implemented in the DSP. The implementation of a conventional and a nonlinear synchronous generator voltage control structure has been presented. These methods were tested in the cases of voltage reference change, mechanical power change and the case of a short circuit on the transmission line.

Key-Words: - Real time simulation, DSP based simulator, synchronous generator, excitation control, nonlinear control

1 Introduction

Testing a controller in complex process control systems demands a real control system or an adequate laboratory model. After engineering the necessary electronic circuits, simulating and implementing the control algorithm, the controller's operation on a real system must be verified. With complex systems, such as a 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 its controller. It is desirable, for technical and economic reasons, to have a simulator, which would simulate the physical behaviors of real, complex systems [1], [2], [3].

The implementation of a control algorithm and the testing of a controller within a synchronous generator's voltage control system by a simulator are presented in this paper. A synchronous generator's dynamic behavior is simulated in real time using a Matlab/Simulink program package. The control algorithm was implemented on a TMS320F2812 digital signal processor (DSP) by Texas Instruments. DSP based simulator (fig. 1) consists of a PC simulating a synchronous generator, connected by a communication channel (through a parallel port) to a DSP into which the control algorithm has been implemented.

The data exchange between the PC and the DSP is carried out by a JTAG (*Join Test Action Group*) emulator through the real- time data exchange interface (RTDX). This kind of simulator for the testing of controller operation in a system is less technically and economically demanding than if the testing was conducted on a lab model, or on a real system. Different control processes can be simulated with the mathematical and simulation models and the input/output signals can be brought directly to the controller, while testing its operation (processor/hardware in the loop simulations).

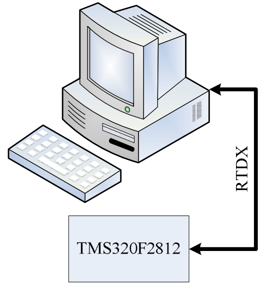

Fig. 1 DSP based simulator

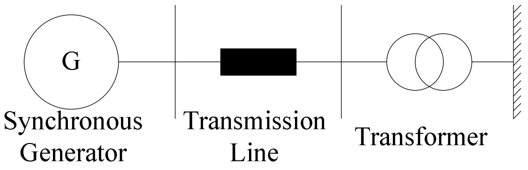

Fig. 2 Synchronous generator connection to AC network

The simulator contains commercial electronic components that are easily accessible and economically acceptable.

In this paper the voltage control system of synchronous generator is examined.

The synchronous generator is connected to a network through a transmission line (fig. 2) (reactance of transmission line is 0.2 p.u.). Fig. 3 shows the generator's voltage control system block scheme.

The generator's voltage control system consists of a proportional excitation current controller and a PI voltage controller which is super-ordinate to it [4], [5]. The control system's input signals are two measured phase currents, two line voltages and the generator's excitation current, while the system's output signal is a PWM signal for an AD/DC converter.

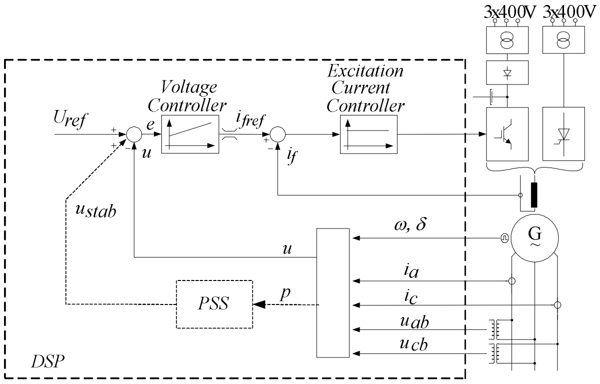

Fig. 3 Generator's voltage control system

2 Simulation model of the synchronous generator

Before implementing and testing controller operation in a real system, it is necessary to make a mathematical and simulation model of the real system. The mathematical model of synchronous generator is determined by the following differential equations [4]:

$$-u_d = r \cdot i_d + \frac{1}{\omega_s} \cdot \frac{d\Psi_d}{dt} + \omega \cdot \Psi_q \tag{1}$$

$$-u_q = r \cdot i_q + \frac{1}{\omega_s} \cdot \frac{d\Psi_q}{dt} - \omega \cdot \Psi_d \tag{2}$$

$$u_f = r_f \cdot i_f + \frac{1}{\omega_s} \cdot \frac{d\Psi_f}{dt} \tag{3}$$

$$0 = r_D \cdot i_D + \frac{1}{\omega_s} \cdot \frac{d\Psi_D}{dt} \tag{4}$$

$$0 = r_Q \cdot i_Q + \frac{1}{\omega_s} \cdot \frac{d\Psi_Q}{dt} \tag{5}$$

The equations defining the relations between the fluxes and currents are:

$$\Psi_d = x_d \cdot i_d + x_{ad} \cdot i_f + x_{dD} \cdot i_D \tag{6}$$

$$\Psi_q = x_q \cdot i_q + x_{qQ} \cdot i_Q \tag{7}$$

$$\Psi_f = x_{ad} \cdot i_d + x_f \cdot i_f + x_{fD} \cdot i_D \tag{8}$$

$$\Psi_D = x_{dD} \cdot i_d + x_{fD} \cdot i_f + x_D \cdot i_D \tag{9}$$

$$\Psi_Q = x_{qQ} \cdot i_q + x_Q \cdot i_Q \tag{10}$$

The aggregate motion equations are:

$$\frac{d\delta}{dt} = (\omega - 1) \cdot \omega_s \tag{11}$$

$$\frac{d\omega}{dt} = \frac{1}{T_m} \cdot (m_m - m_e) \tag{12}$$

The electromagnetic torque of the generator is determined by equation:

$$m_e = \Psi_q \cdot i_d - \Psi_d \cdot i_q \tag{13}$$

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

$$u_d = i_d \cdot r_e + \frac{x_e}{\omega_s} \cdot \frac{di_d}{dt} + \omega \cdot x_e \cdot i_q + u_{sd} \tag{14}$$

$$u_q = i_q \cdot r_e + \frac{x_e}{\omega_s} \cdot \frac{di_q}{dt} - \omega \cdot x_e \cdot i_d + u_{sq} \tag{15}$$

$$u_{sd} = U_s \cdot (-\sin\delta) \tag{16}$$

$$u_{sq} = U_s \cdot \cos\delta \tag{17}$$

The mathematical model of a synchronous generator connected to a power system is simulated in the Matlab/Simulink program tool.

In the first case the simulation model (fig. 4) includes a proportionally integral (P.I.) voltage controller and a proportional (P) generator excitation current controller.

After performing the tests on a simulation model it is necessary to implement the control algorithms into the existing excitation system. Nowadays, digital signal processors (DSP) are often used as control units in the excitation control system of a synchronous generator 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 using a high-level languages (C/C++, Java, etc) or through assembly languages. This demands additional knowledge of DSP programming.

Controller operation must be verified after implementing the control algorithm into the DSP. A laboratory model of a generator's voltage control system is complex and may not be profitable. Also, it is rarely possible to perform this kind of voltage control system testing on the real power plant, because it demands that the power plant operation be stopped. So, in the second case the control structure is implemented in the DSP system and then compared with the first case, when the control structure is simulated in Matlab/Simulink.

3 Simulation model of the voltage control system

The simulation model of a synchronous generator's voltage control system (fig. 4) describes the given system well. Various control algorithms can be tested on this model, and the physical behaviors of the system with different control algorithms can be observed. The 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-bite, 16-bite), types of data the processor works with (fixed-point or floating-point), speed of transfer and of data processing, signal filtration in cases of analog- digital conversion.

Besides, this model is not suitable for the direct implementation of the control algorithm into the DSP, because it is simulated using the variable-step ode45 (Dormand-Prince) method. It is impossible to know the exact state of the simulated physical variables at every moment.

The simulation model at hand cannot be simulated using any fixed-step methods due to algebraic loops. That is why the control system controller in the simulation model must be a discrete one.

The PI voltage controller (fig. 5) and the P excitation current controller (fig. 6) from the synchronous power plant simulation model must be realized in the discrete domain (fig. 7), so the algorithm can be implemented into the DSP. The voltage reference signal, as well as the measured voltage and measured excitation current signals have been made discrete using the Zero-Order Hold function.

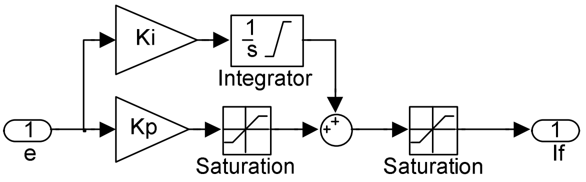

Fig. 5 PI voltage controller

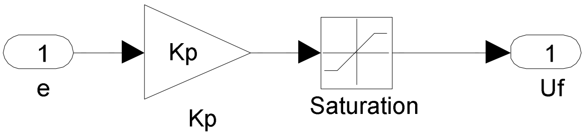

Fig. 6 P excitation current controller

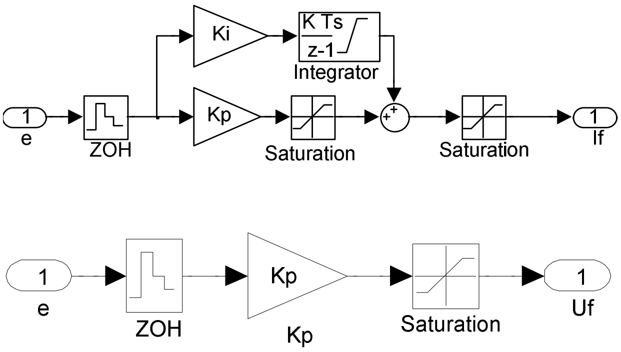

Fig. 7 - PI voltage controller and P excitation current controller in discrete form

Simulation tests of the generator's voltage control system's operation have been done for both the cases of generator's reference voltage step-change and of a short circuit on transmission line (fig. 2).

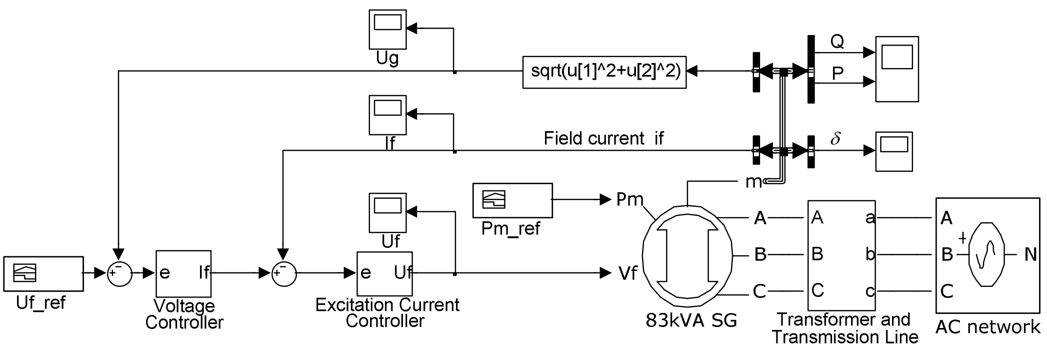

Fig. 4 Simulation model of synchronous generator's voltage control system

4 Using simulator for implementing and testing of algorithms

Several changes need to be made for implementing the control algorithm into the DSP system. The simulator works with a 32-bite fixed-point TMS320F2812 DSP. Therefore, all the floating-point input signals must be converted into fixed-point signals. The voltage reference signal, measured voltage and measured excitation current signals have been converted from floating-point into fixed-point signals using the IQMath blocks (Float to IQN).

Fig. 8 shows the synchronous generator control algorithm implemented in the simulator based on the DSP. A PID controller block from the DMC library was used for the synchronous generator's PI voltage control and P excitation current control.

Control algorithms with the simulator are block-programmed using Matlab/Simulink R2008a (with TC2 Target Support Package) [6], [7], [8].
Using Real Time Workshop, Embedded Link IDE CC, the block algorithm of the synchronous generator's excitation system is automatically translated into C/C++, and also automatically lowered into the DSP. The communication between the PC and the DSP takes place via a parallel communication port using the RTDX interface [9].

4.1 Implementing of conventional algorithm

The generator's voltage control system's operation has been tested for the cases of reference voltage step change and of a three-phase short circuit on the transmission line.

Fig. 9 show the generator responses in the case of a short circuit which happened at 0,3 seconds and lasted 100 ms, for a system with a simulated discrete and DSP implemented controller.

Fig. 10 show the generator responses for generator's reference voltage change from the initial value of 1 p.u. to the value of 0,8 p.u., for a system with a simulated discrete and DSP implemented controller.

The simulation model controlled by the simulator (DSP) in real time has an 0,8 ms delay compared to a case, where the simulated model of the controlled system is performed on a PC. The simulator's delay compared to a synchronous generator's discrete excitation system is caused by the delay in data exchange between the DSP and the PC.

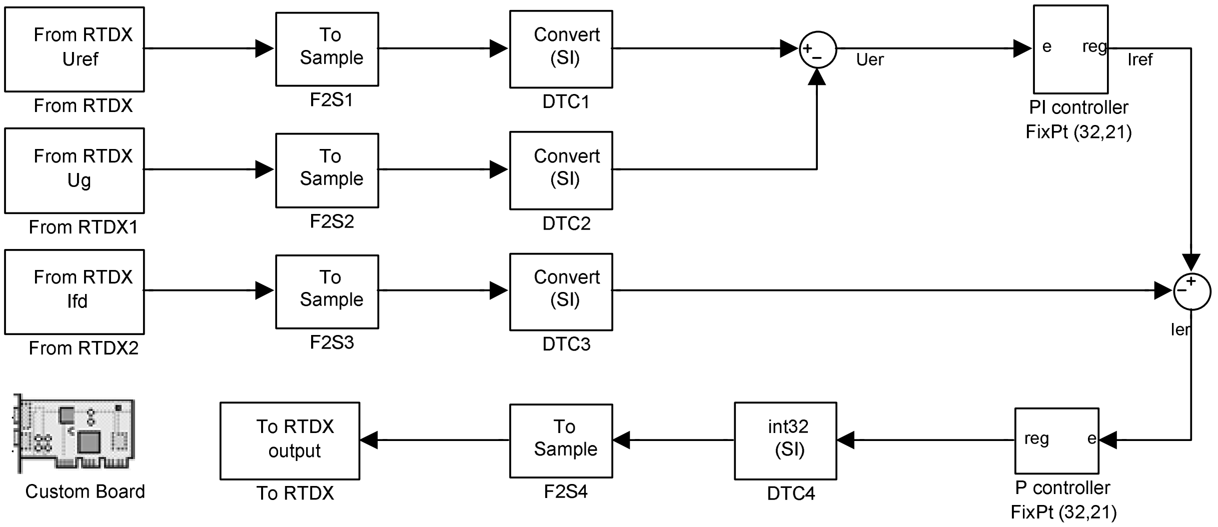

Fig. 8 Synchronous generator control algorithm on DSP based simulator

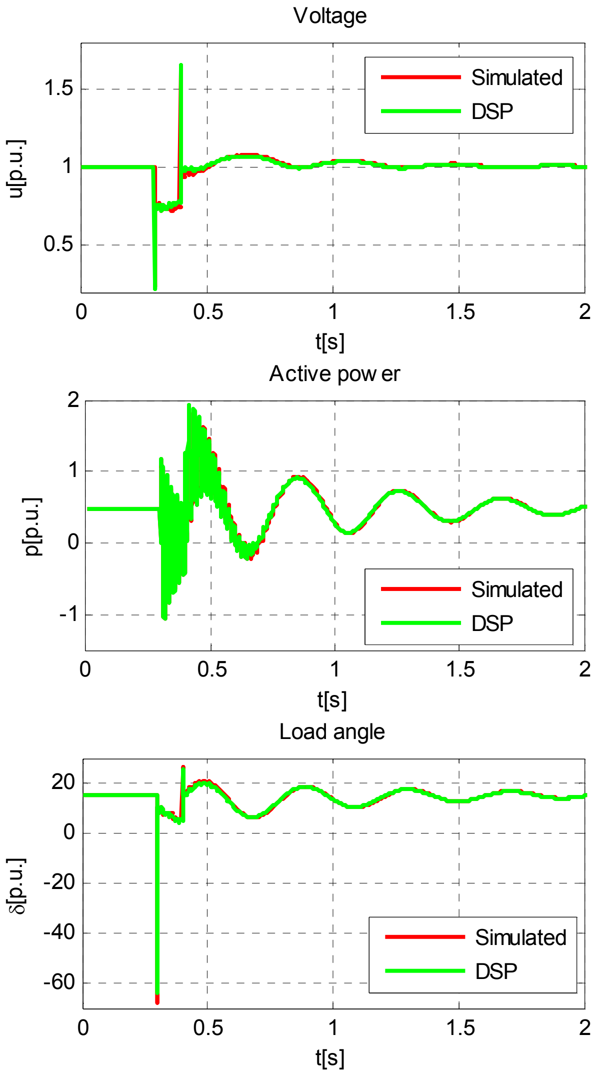

Fig. 9 Synchronous generator's voltage, active power and load angle for short circuit with simulated discrete and implemented in DSP PI voltage controller and P excitation current controller

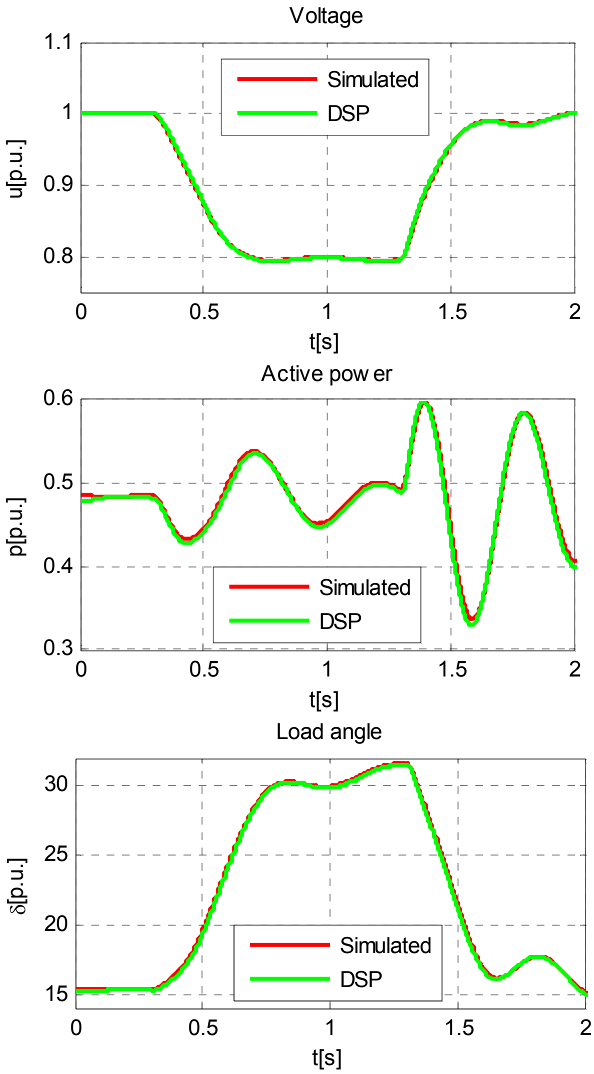

Fig. 10 Synchronous generator's load angle for generator's reference voltage change with simulated discrete and implemented in DSP PI voltage controller and P excitation current controller

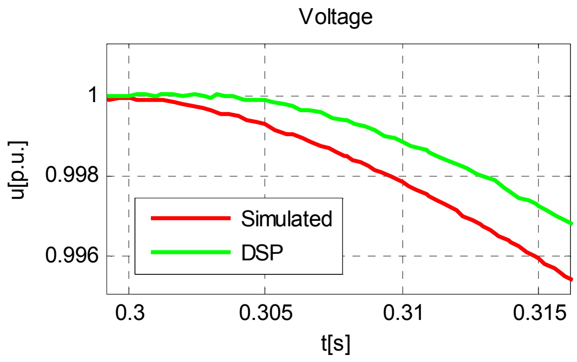

Fig. 11 Time delay of the simulator

4.2 Implementing of nonlinear algorithm

The parameters and characteristics of a conventional voltage regulator are determined based on a linearized synchronous generator model operating at a specific work point so this regulator is not robust to generator work point changes, i.e. to system structure changes (transmission line falling out, short circuit on a transmission line 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 structures and synchronous generator excitation system control algorithms. Starting from the demands of the power system makes on the power aggregate, i.e. on generator excitation, a new, nonlinear excitation controller has been developed and implemented by using Lyapunov's direct stability method. The nonlinear regulator not only keeps the voltage on generator clamps equal to the reference voltage, but also damps the electro mechanic oscillations of the power unit.

Lyapunov's direct method [10], [11], [12] was used to develop the nonlinear voltage regulator as well as a third order mathematical model of a hydrogenerator (active resistances of the stator coils and transient processes in damping coils were neglected), which is connected to an AC network via transformer and transmission line (fig. 2). Vector diagram of a hydrogenerator connected to AC network is presented on the fig. 12.

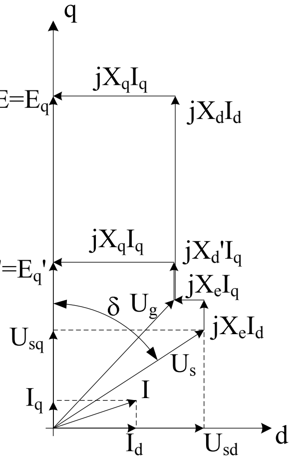

Fig. 12 Vector diagram of hydrogenerator connected to AC network

The mathematical model of synchronous generator connected to AC network is given by [1], [2], [11], [12]:

$$\frac{d\delta}{dt} = (\omega - 1)\cdot \omega_s \tag{18}$$

$$\frac{d\omega}{dt} = \frac{1}{T_m}\cdot (p_m - p_e) \tag{19}$$

$$\frac{dE_q'}{dt} = \frac{1}{T_{d0}'}\cdot \left(E_f - i_f \cdot x_{ad}\right) \tag{20}$$

where δ is the load angle, ω rotation speed and E_q' transient induced voltage in the q axis q osi. P_e denotes generator active power which comes to:

$$\begin{aligned} p_e = {} & \frac{E_q' \cdot U_s}{x_d' + x_e}\cdot \sin(\delta) \\ & + \frac{U_s^2}{2}\cdot \left(\frac{x_d' - x_q}{(x_{d'} + x_e)\cdot (x_q + x_e)} \right)\cdot \sin(2\cdot\delta) \end{aligned} \tag{21}$$

Lyapunov's direct method is one of the more important tools for analyzing stability of nonlinear systems today. Lyapunov's methods are also used in the synthesis of nonlinear control algorithms, known as Control Lyapunov Function (CLF) [13], [14], [15], [16], [17]. The existance of the CLF is both a necessity and condition enough for system stability. Using the CLF can lead to the development of varius rules of control which will asymptotically stabilize the system. The CLF's greatest disadvantage is – there is no exact way to find a CLF for a nonlinear system.

Further on, a control algorithm has been developed for the control of a synchronous generator excitation system, which will confirm the system's stability according to Lyapunov.

Assuming Lyapunov's function (22), where is the error between voltage reference value and the real voltage value on generator clamps (23):

$$V = \frac{1}{2}\cdot e^2 \tag{22}$$

$$e = U_{ref} - u \tag{23}$$

Adding (23) into (22), and differentiating the equation (22) will lead to:

$$\frac{dV}{dt} = e \cdot \frac{du}{dt} \tag{24}$$

Supstitution of generator voltage $u = \sqrt{u_d^2 + u_q^2}$ to the equation (24) will lead to:

$$\frac{dV}{dt} = \frac{e}{u}\cdot \left(u_d \cdot \frac{du_d}{dt} + u_q \cdot \frac{du_q}{dt} \right) \tag{25}$$

From the generator's vector diagram (fig 12), voltages u_d i u_q can be calculated:

$$u_d = U_s \cdot \sin(\delta)\cdot \frac{x_q}{x_q + x_e} \tag{26}$$

$$u_q = E_q' \cdot \frac{x_e}{x_d' + x_e} + U_s \cdot \cos(\delta)\cdot \frac{x_d'}{x_d' + x_e} \tag{27}$$

respectively:

$$\begin{aligned} \frac{du_d}{dt} & = U_s \cdot \frac{x_q}{x_q + x_e}\cdot \cos(\delta)\cdot \frac{d\delta}{dt} \\ & = U_s \cdot \frac{x_q}{x_q + x_e}\cdot \cos(\delta)\cdot \omega_s \cdot \Delta\omega \end{aligned} \tag{28}$$

$$\begin{aligned} \frac{du_q}{dt} & = \frac{dE_q'}{dt}\cdot \frac{x_e}{x_d' + x_e} \\ & \quad - U_s \cdot \sin(\delta)\cdot \frac{x_d'}{x_d' + x_e}\cdot \frac{d\delta}{dt} \\ & = \frac{1}{T_{d0}'}\cdot \left(E_f - i_f \cdot x_{ad}\right)\cdot \frac{x_e}{x_d' + x_e} \\ & \quad - U_s \cdot \sin(\delta)\cdot \frac{x_d'}{x_d' + x_e}\cdot \omega_s \cdot \Delta\omega \end{aligned} \tag{29}$$

Adding the equations (28) and (29) to the equation (25) will lead to:

$$\begin{aligned}\frac{dV}{dt} = \ & \frac{e}{u}\Bigg[u_d \frac{x_q}{x_e + x_q} U_s \cos(\delta)\omega_s \Delta\omega \\ & + u_q \frac{1}{T_{d0}'} E_f \frac{x_e}{x_d' + x_e} \\ & + u_q \left(-\frac{1}{T_{d0}'} i_f x_{ad} \frac{x_e}{x_d' + x_e} \right. \\ & \left. - \frac{x_d'}{x_d' + x_e} U_s \sin(\delta)\omega_s \Delta\omega \right)\Bigg]\end{aligned} \tag{30}$$

Control rule has been selected:

$$\begin{aligned}E_f = \ & -T_{d0}' \frac{x_d' + x_e}{x_e} \frac{1}{u_q} \Bigg[K_1 e \\ & + K_2 u_d \frac{x_q}{x_e + x_q} U_s \cos(\delta)\omega_s \Delta\omega \\ & + K_3 u_q \left(-\frac{1}{T_{d0}'} i_f x_{ad} \frac{x_e}{x_d' + x_e} \right. \\ & \left. - \frac{x_d'}{x_d' + x_e} U_s \sin(\delta)\omega_s \omega \right)\Bigg]\end{aligned} \tag{31}$$

where K_1, K_2 i K_3 are parameters which force Lyapunov's function differentiation to be negative at every generator work point.

Implementing control rule (31) into the equation (30) will lead to:

$$\begin{aligned}\frac{dV}{dt} = \ & -K_1 \frac{e^2}{u} + \frac{e}{u}\Bigg[u_d \frac{x_q}{x_e + x_q} U_s \cos(\delta) \cdot \\ & \cdot \omega_s \Delta\omega (1 - K_2) + u_q Y (1 - K_3)\Bigg]\end{aligned} \tag{32}$$

where:

$$\begin{aligned}Y = \ & -\frac{1}{T_{d0}'} i_f x_{ad} \frac{x_e}{x_d' + x_e} \\ & - \frac{x_d'}{x_d' + x_e} U_s \sin(\delta)\omega_s \Delta\omega\end{aligned} \tag{33}$$

In order for the system to be stable according to Lyapunov, the following must be valid at every generator work point: $\frac{dV}{dt} < 0$. It is obvious from the first part of equation (32) that $-K_1 \frac{e^2}{u} < 0$ is valid for any $K_1 > 0$ (generator voltage $u > 0$ at every generator work point), whereas the second part depends on $\Delta\omega$, δ, u_d and u_q. If the differentiation of Lypunov's function (32) is to be negative, the following equation must be valid:

$$\begin{aligned}& -K_1 \frac{e^2}{u} + \frac{e}{u}\Bigg[u_d \frac{x_q}{x_e + x_q} U_s \cos(\delta) \cdot \\ & \cdot \omega_s \Delta\omega (1 - K_2) + u_q Y (1 - K_3)\Bigg] < 0\end{aligned} \tag{34}$$

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:

$$\frac{dV}{dt} \approx -K_1 \frac{e^2}{u} < 0 \tag{35}$$

Although it has been assumed that $\Delta\omega \approx 0$, the simulation results stated in the following chapter show that the work of the presented control algorithm, the structure of which is shown in figure 15, is satisfactory even in cases of larger disturbances.

4.2 Comparison of the conventional and nonlinear control structure

Figures 13, 14 and 16 show the comparison of the implemented conventional and nonlinear control structure for generator reference voltage change from the initial value of 1 p.u. to the value of 0,8 p.u.; for mechanical power change from 0.5 to 0.8 p.u. and then back to 0.5 pu at generator voltage 0.9 p.u.; and for a short circuit on the one transmission line. Presented results showed that the nonlinear control structure achieves better performance than conventional control structure.

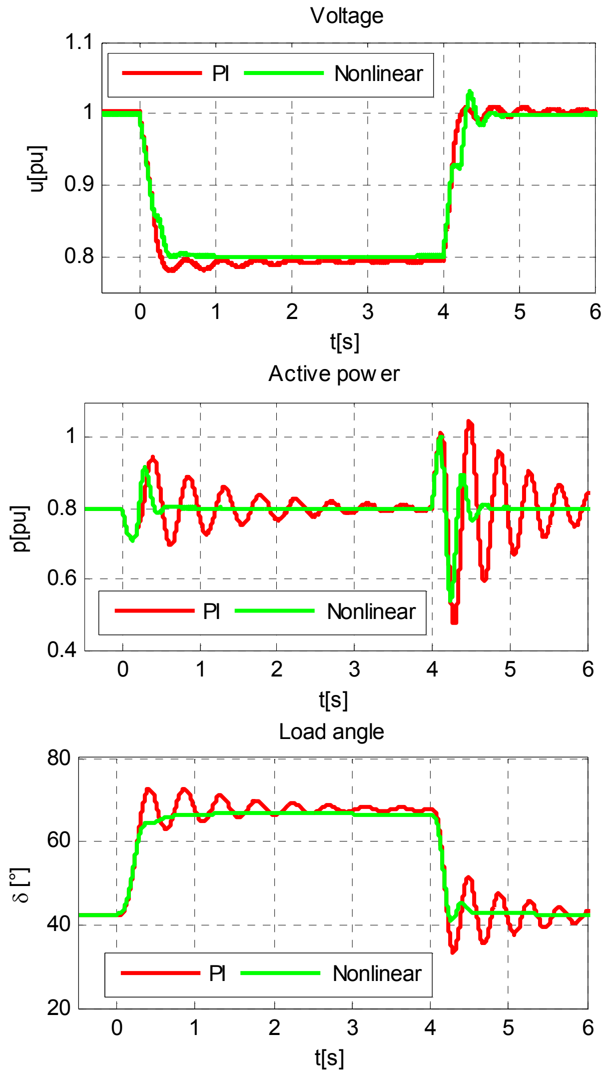

Fig. 13 Synchronous generator's responses for voltage reference change for implemented PI control structure and nonlinear control structure

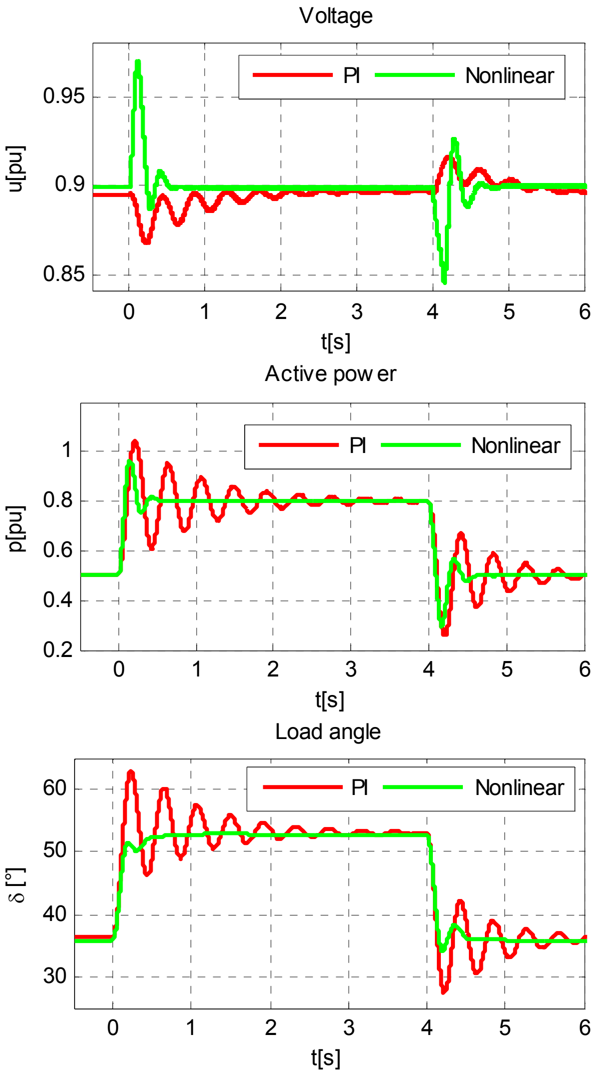

Fig. 14 Synchronous generator's responses for mechanical power change for implemented PI control structure and nonlinear control structure

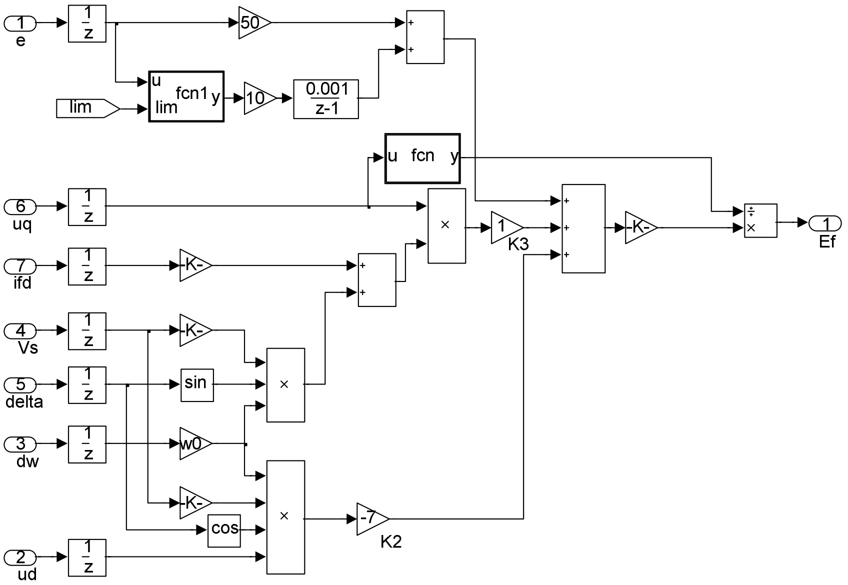

Fig. 15 Nonlinear voltage control structure

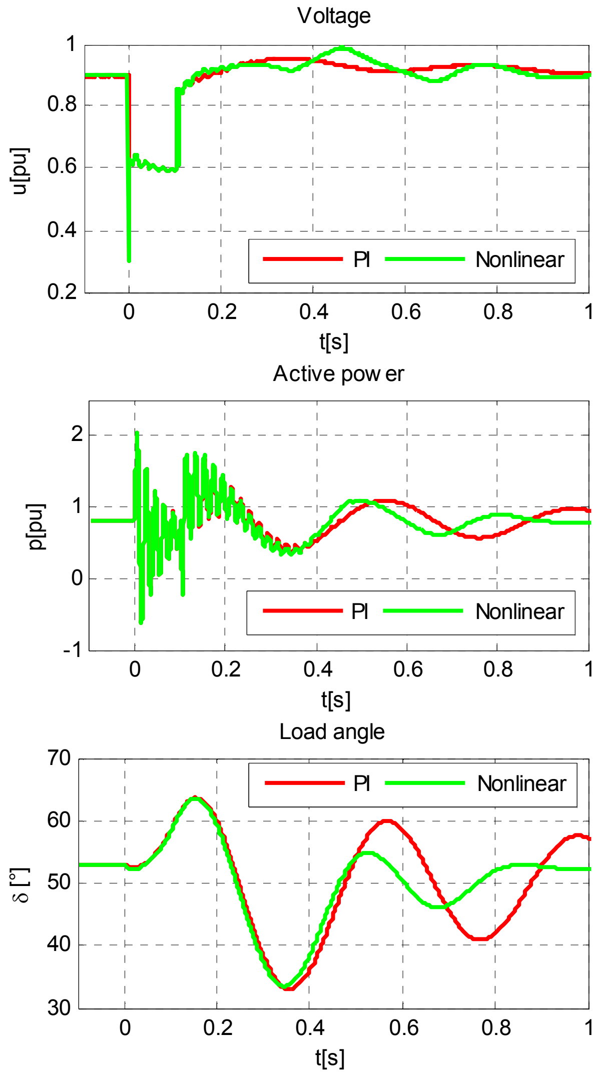

Fig. 16 Synchronous generator's responses for short circuit on transmission line for implemented PI control structure and nonlinear control structure

5 Conclusion

DSP based simulator in real time enables faster processes of engineering, implementing and verifying control algorithms not only for the voltage control system of a synchronous generator, but also for other systems able of having mathematical and simulation models. The engineering of control algorithms is based on block programming, so the program code is automatically generated, translated and downloaded into the DSP using Real Time Workshop and Matlab Embedded Link IDE CC. The simulator verifies the control algorithm by a simulation in real time, where the simulated model of the controlled system is performed on a PC. This paper shows a comparison in the case when both the system model and the control structure are simulated and for a case when the model is simulated on a computer and the control structure implemented in the DSP. It has been concluded that in the case when the control structure implemented in the DSP there is a 0,8ms time delay. Also, the implementation of a conventional and a nonlinear synchronous generator voltage control structure has been presented. These methods were tested in the cases of voltage reference change, mechanical power change and the case of a short circuit on the transmission line. The nonlinear structure has shown better results as the conventional structure.

List of symbols

u_d	d-axe component of the generator terminal voltage
u_q	q-axe component of the generator terminal voltage
u_f	excitation voltage
u_s	infinite busbar voltage
u_{sd}	d-axe component of the infinite busbar voltage
u_{sq}	q-axe component of the infinite busbar voltage
i_d	d-axe component of the generator stator current
i_q	q-axe component of the generator stator current
i_f	field current
i_D	d-axe field damper current
i_Q	q-axe field damper current
r	generator stator resistance
r_f	excitation resistance
r_D	d-axe damper resistance
r_Q	q-axe damper resistance
ω	generator rotor speed
ω_s	synchronous speed
Ψ_d	d-axe flux linkage
Ψ_q	d-axe flux linkage
Ψ_f	field flux linkage
Ψ_D	d-axe field damper flux linkage
Ψ_Q	q-axe field damper flux linkage
x_d	d-axe synchronous reactance
x_q	q-axe synchronous reactance
x_{fd}	field reactance
x_D	d-axe damper reactance
x_Q	q-axe damper reactance
x_d'	d-axe transient reactance

x_{ad}	armature reaction reactance
$x_e = x_T + x_L$	transformer and transmission line reactance
$r_e = r_T + r_L$	transformer and transmission line resistance
δ	rotor angle
m_m	mechanical torque
m_e	electromagnetic torque
p_m	mechanical power
p_e	electromagnetic power
T_m	mechanical time constant
$E_q{}'$	q-axe component of transient EMF
E_f	field voltage

Appendix A
The synchronous generator's rated parameters are:

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

Appendix B
Controllers' parameters are:

Voltage controller	
Kp	10
Ki	15
Excitation current controller	
Kp	10
Nonlinear controller	
K1	50
K2	-7
K3	1

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