Modelling and simulation of synchronous machine transient analysis using SIMULINK

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Abstract This work describes a method which illustrates the benefits of the visual aspects of MATLAB/SIMULINK for educational purposes. The method is specially developed for transient analysis of synchronous machines given by a simplified model. Details such as the exciter circuit, turbine and governor systems of a synchronous machine which is linked to an infinitive bus through two equivalent lines are given and this system is implemented in SIMULINK. The considered synchronous machine has a rated power capacity of 160 MVA and rated voltage of 15 kV.

Keywords MATLAB; modelling; SIMULINK; synchronous machine

List of symbols

P_e : Electrical output power
V_t : Generator terminal voltage
V_{td} : d axis component of terminal voltage
V_{tq} : q axis component of terminal voltage
I_d : d axis armature current
I_q : q axis armature current
E'_d : d axis transient voltage
E'_q : q axis transient voltage
T'_{d0} : d axis open circuit time constant
T'_{q0} : q axis open circuit time constant
E_{fd} : d axis field voltage
K_E : Exciter gain
T_E : Exciter time constant
V_s : Stabilizing transformer voltage
K_F : Stabilizer circuit gain
T_{FE} : Stabilizer circuit time constant
T_{SR} : Speed relay time constant
T_{SM} : Servomotor time constant
T_{CH} : Steam chest time constant
T_{RH} : Reheater time constant
K_{RH} : Reheater gain
s : Laplace derivation operator
P_r : Speed relay output power
P_h : Servomotor output power
P_c : Steam chest output power
P_m : Generator input power
K_G : Speed relay gain
δ : Rotor angular position
ω : Angular speed
ω_0 : Base angular speed
ω_r : Governor reference angular speed
D : Damping coefficient
M : Inertia constant of generator
R_a : Armature resistance
R_e : Equivalent resistance of transmission lines
x_e : Equivalent reactance of transmission lines
x_d : Synchronous reactance
x'_d : Transient reactance
x_q : q axis reactance of generator
V : Infinitive bus voltage
P : Real power
Q : Reactive power
Δ : Change from nominal values
V_{tr} : Reference value of the terminal voltage

Simulation of synchronous machines can be done using various simulation tools, one of which is electromagnetic transient programs (EMTP).[1] In this work, SIMULINK/MATLAB is favoured over other tools in modelling the dynamics of a synchronous machine. The SIMULINK program in MATLAB is used to obtain a schematic model of a synchronous machine by means of basic function blocks. This approach is pedagogically better than using a compilation of program code as in other software programs found in the literature.[2,3] The library of SIMULINK software programs includes function blocks which can be linked and edited to model the dynamics of a system by using menu commands found on the keyboard.

The synchronous machine's dynamic model equations in the Laplace domain can be created by connecting appropriate function blocks. In order to simulate the detailed transient analysis of the synchronous machine, addition of new sub-models is needed to model the operation of various control functions. These sub-models are used in the calculation of various values related to the synchronous machine such as the steady state, exciter loop, turbine governor model and the currents.

Synchronous machine model constructed using SIMULINK

A model of the synchronous machine with appropriate degrees is given in this work for a transient stability investigation.[3,4] The considered single machine-infinitive bus system is given in Fig. 1.

Electrical and mechanical sub-model of the synchronous machine

For transient stability analysis, the synchronous machine model for generator operating is considered as a classical fourth-degree model given below:

Electrical part:

$$E'_d = \frac{x'_d - x_q}{1 + sT'_{q0}} I_q \tag{1}$$

$$E'_q = \frac{x'_d - x_d}{1 + sT'_{d0}} I_d + \frac{E_{fd}}{1 + sT'_{d0}} \tag{2}$$

Mechanical part:

$$\Delta\omega = \frac{1}{D + sM}(P_m - P_e) \tag{3}$$

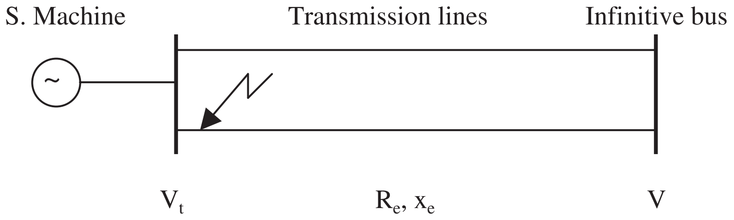

Fig. 1 *The considered single machine-infinitive bus system.*

$$\delta = \omega_0 \frac{\Delta\omega}{s} \tag{4}$$

Turbine and governor system:

$$\Delta P_r = \frac{K_G}{1 + sT_{SR}} \Delta\omega \tag{5}$$

$$\Delta P_h = \frac{1}{1 + sT_{SM}} \Delta P_r \tag{6}$$

$$\Delta P_c = \frac{1}{1 + sT_{CH}} \Delta P_h$$

$$\Delta P_m = \frac{sK_{RH} T_{RH}}{1 + sT_{RH}} \Delta P_c \tag{7}$$

Exciter:

$$E_{fd} = \frac{K_E}{1 + sT_E} (V_{tr} - V_t - V_s) \tag{8}$$

$$V_s = \frac{sK_F}{1 + sT_{FE}} E_{fd} \tag{9}$$

Terminal equations:

$$V_{td} = E'_d - R_a I_d - x'_d I_q = -V_0 \sin\delta + R_e I_d + x_e I_q \tag{10}$$

$$V_{tq} = E'_q - R_a I_q + x'_d I_d = V_0 \cos\delta + R_e I_q - x_e I_d \tag{11}$$

$$P_e = E'_d I_d + E'_q I_q \tag{12}$$

The exciter is represented by a second-order dynamical model as in Fig. 2. The sub-model has two inputs, V_{tr} and V_t, reference and instantaneous values of terminal voltage, respectively and one output E_{fd} in per-unit values. Moreover, the sub-model of the mechanical part is represented by a dynamical model as in Fig. 3. The considered system, given in Fig. 3, includes a turbine and governor sub-system and the blocks of the relations among rotor angle δ, deviation of angular speed $\Delta\omega$, and

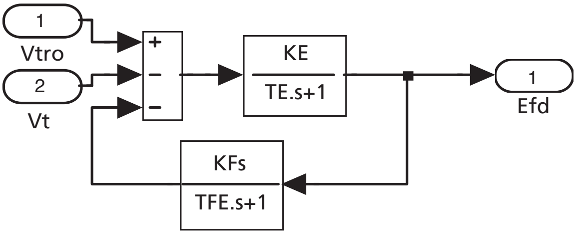

Fig. 2 *The sub-model of the exciter system.*

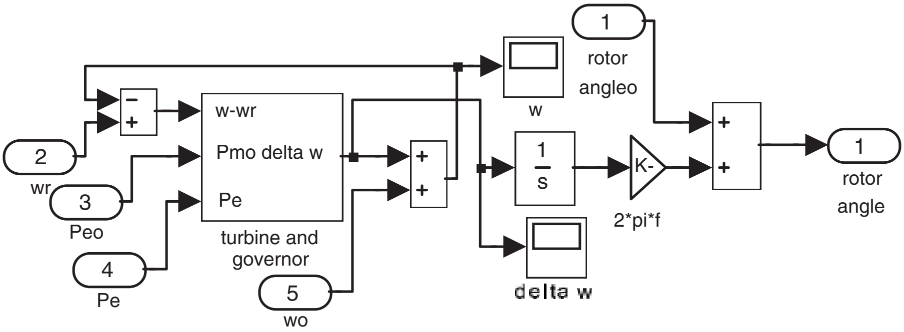

Fig. 3 *The sub-model of the mechanical part.*

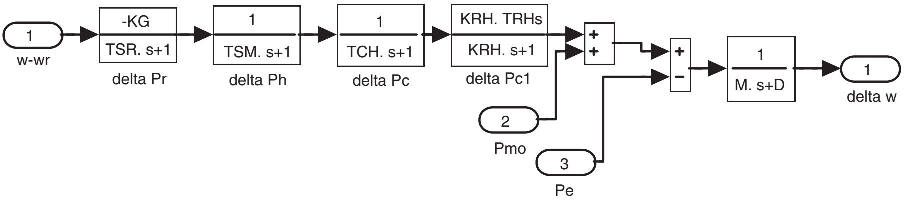

Fig. 4 *Turbine and governor system configuration.*

steady state value of angular speed, ω_0, as given in equation (4). The sub-model includes five inputs, steady state value of rotor angle in radian, reference value of angular speed, the steady state and instantaneous values of real electrical power and steady state value of angular speed, in per-unit values. It has one output rotor angle in radians. The sub-model of the turbine and governor system is represented in Fig. 4.[5]

The sub-model contains three inputs, the difference between the reference value and instantaneous value of angular speed, the steady state value of mechanical power, instantaneous value of electrical power, in per-unit, and one output, the deviation of angular speed in per-unit. The sub-model in Fig. 5 represents continuous operation of the electrical parts of the machine. The initial values which will be used until a fault occurs are provided by four switches in the sub-model. The inputs of the sub-model are δ, E_{d0}', E_{fd}, V_{t0}, E_{q0}', P_{e0}, V_0, R_e, x_e, and the outputs are V_t, P_e. The sub-models for currents, terminal voltage and real electrical power are given in Figs 6 to 8, respectively.

Steady state values of the synchronous generator

The steady state values are calculated separately according to the block diagram of Fig. 9.

The function blocks given in Fig. 9 which correspond to initial values of current, load angle, rotor angle, electromotor force in the machine, terminal voltage, real

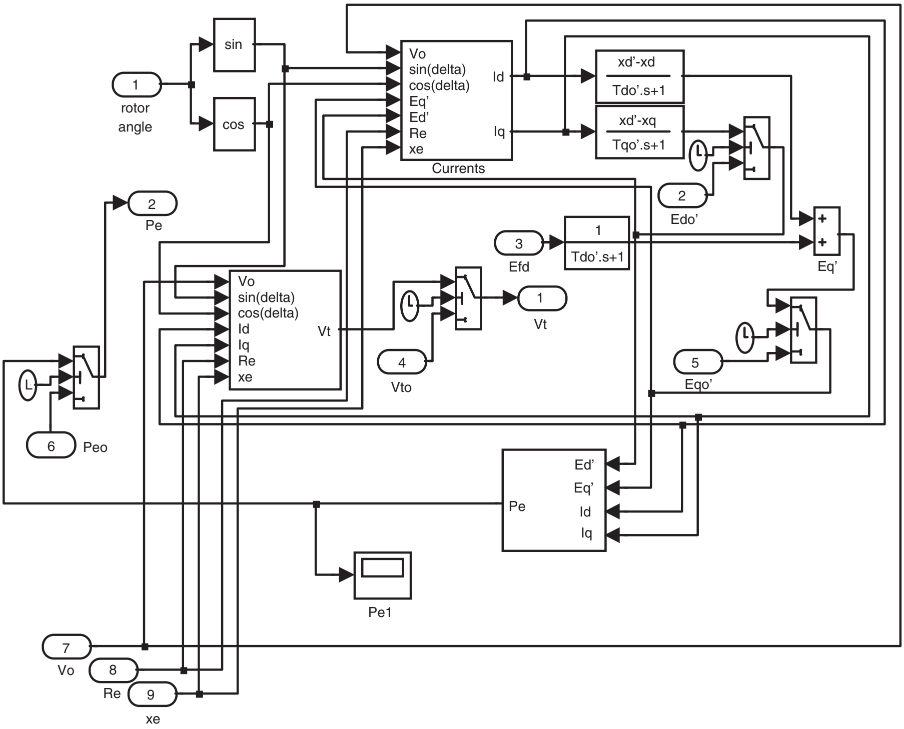

Fig. 5 *The sub-model of continuous operation of the synchronous machine.*

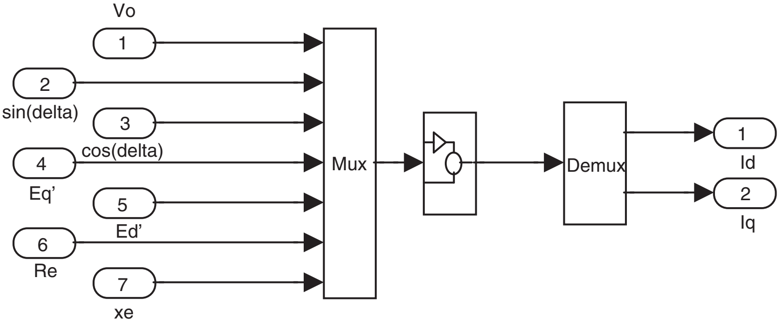

Fig. 6 *The sub-model of current calculated.*

power, exciter voltage, and reference terminal voltage are calculated using the equations given below:

$$I_0 = \frac{\sqrt{P_0^2 + Q_0^2}}{V_0} \tag{13}$$

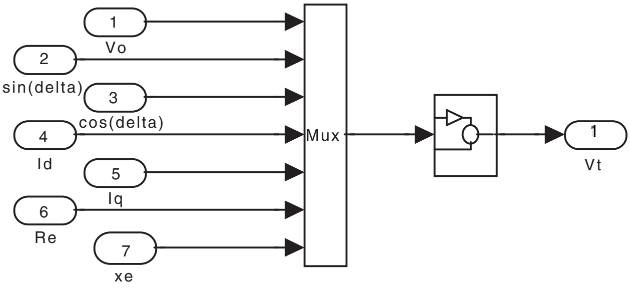

Fig. 7 *The sub-model for calculation of terminal voltage.*

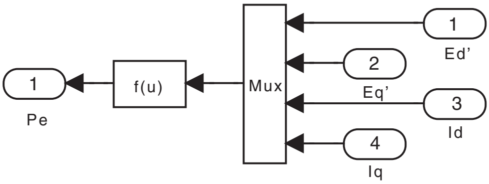

Fig. 8 *The sub-model for calculation of electrical power.*

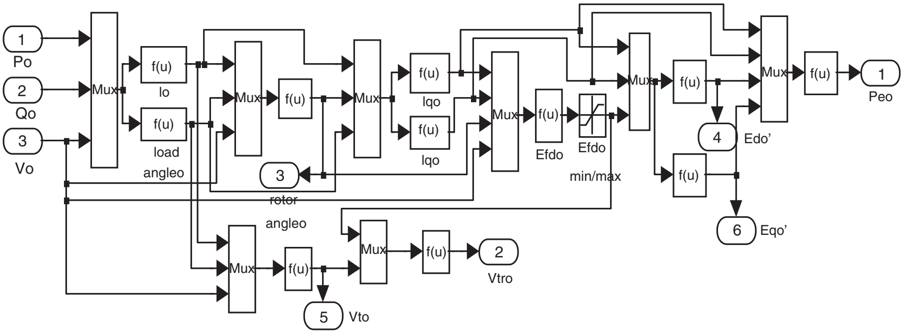

Fig. 9 *The steady-state sub-model of the synchronous machine.*

$$\varphi_0 = \arctan\frac{Q_0}{P_0} \tag{14}$$

$$\delta_0 = \arctan\frac{I_0\left(x_q + x_e\right)\cos\varphi_0 - I_0(R_a + R_e)\sin\varphi_0}{V_0 + I_0(R_a + R_e)\cos\varphi_0 + I_0\left(x_q + x_e\right)\sin\varphi_0} \tag{15}$$

$$I_{d0} = -I_0\sin\left(\delta_0 + \varphi_0\right) \tag{16}$$

$$I_{q0} = I_0\cos\left(\delta_0 + \varphi_0\right) \tag{17}$$

$$E_{fd0} = V_0\cos\delta_0 + (R_a + R_e)I_{q0} - (x_d + x_e)I_{d0} \tag{18}$$

$$V_{t0} = \sqrt{\left(V_0 + R_e I_0 \cos\varphi_0 + x_e I_0 \sin\varphi_0\right)^2 + \left(x_e I_0 \cos\varphi_0 - R_e I_0 \sin\varphi_0\right)^2} \tag{19}$$

$$E'_{d0} = -\left(x_q - x'_d\right) I_{q0} \tag{20}$$

$$E'_{q0} = E_{fd0} + (x_d - x'_d) I_{d0} \tag{21}$$

$$P_{e0} = E'_{d0} I_{d0} + E'_{q0} I_{q0} \tag{22}$$

$$P_{m0} = P_{e0} \tag{23}$$

$$V_{tr} = \frac{E_{fd0}}{K_E} + V_{t0} \tag{24}$$

The reference value of the terminal voltage of the synchronous machine is given in the last equation above.

Simulation model of the synchronous generator

The complete model of the synchronous machine used in the simulation is given in Fig. 10.

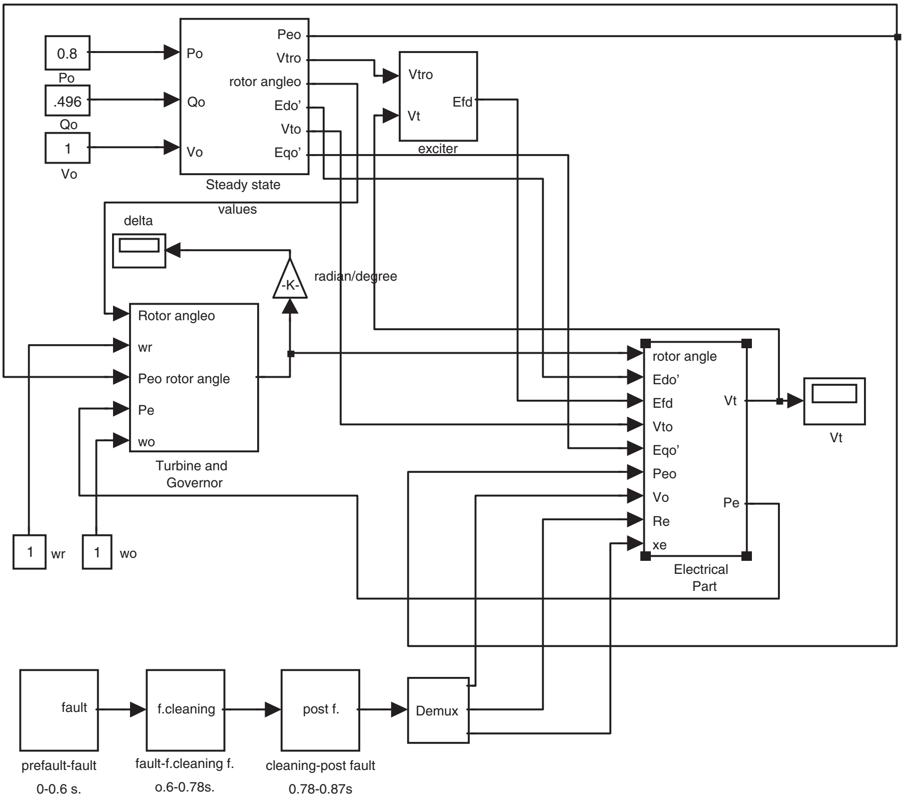

Fig. 10 *The complete model of the system in SIMULINK.*

For transient stability analysis of a synchronous machine, it is assumed that a three-phase short-circuit at the sending terminal of one of the parallel lines has occurred at 0.6 s and the fault has continued until 0.78 s. The fault is cleared by switching the faulted line between 0.78 and 0.87 s and then the system is returned to the pre-fault configuration. These cases are represented by switch blocks in the model given in Fig. 10. The simulation lasts 10 s. Only one of the switch blocks given in Fig. 11(a) and (b) is explicitly given as an example configuration. The parameters of the system are given in the Table 1.

The sub-system in Fig. 11(a) initially gives first operation values to the system via out 3. After a period which is determined by adjusting the clock, the switch changes and new parameter values are collected from out 1. The switch configuration is similar for other operating conditions.

The simulation results are given in Figs 12–15. Fig. 12 represents the deviation

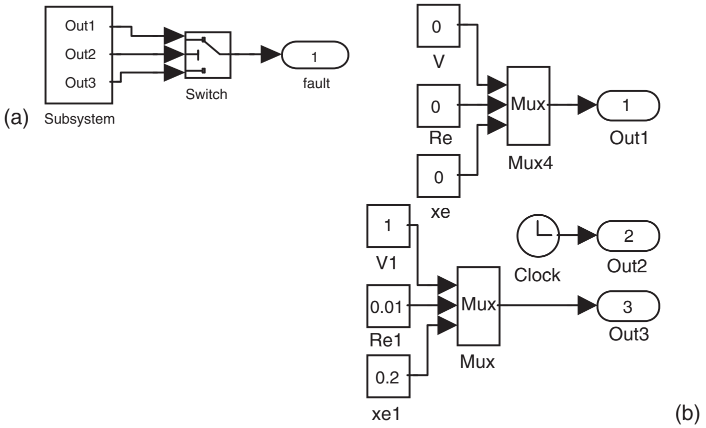

Fig. 11 *(a) The switch configuration; (b) inner details of the considered switch.*

TABLE 1 *The parameter values of the synchronous machine have a capacity of 160 MVA rated power, 15 kV rated voltage*

P_0	: 0.8	x_d'	: 0.245	T_E	: 0.05 s	T_{RH}	: 8 s
Q_0	: 0.496	x_e	: 0.2	K_F	: 0.025	T_{CH}	: 0.05 s
V_0	: 1	T_{d0}'	: 5.9 s	T_{FE}	: 1 s	T_{SR}	: 0.1 s
R_a	: 0.001096	T_{q0}'	: 0.075s	D	: 0	K_G	: 3.5
R_e	: 0.01	K_E	: 400	M	: 4.74	T_{SM}	: 0.2 s
x_d	: 1.7	E_{fdmin}	: –4.5	K_{RH}	: 0.3	ω_r	: 1
x_q	: 1.64	E_{fdmax}	: 4.5	ω_0	: 1		

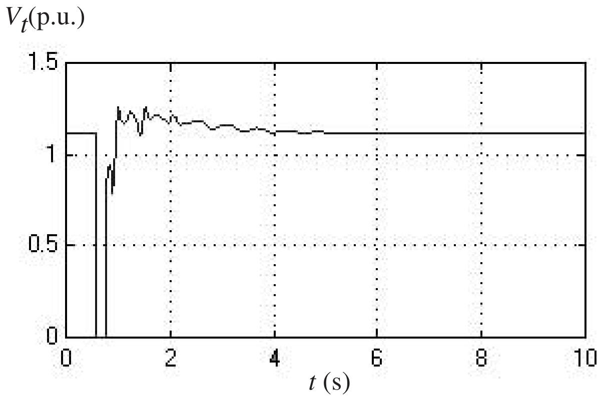

Fig. 12 *The deviation of the terminal voltage.*

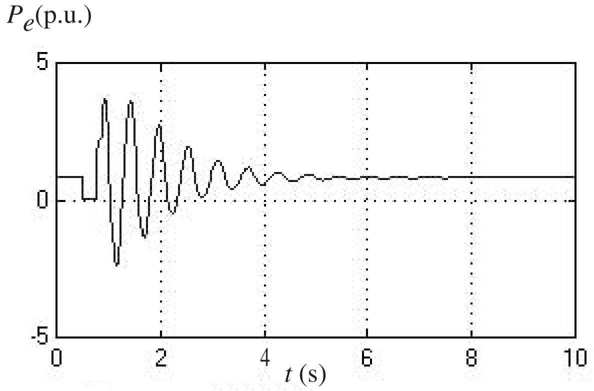

Fig. 13 *The deviation of the electrical power.*

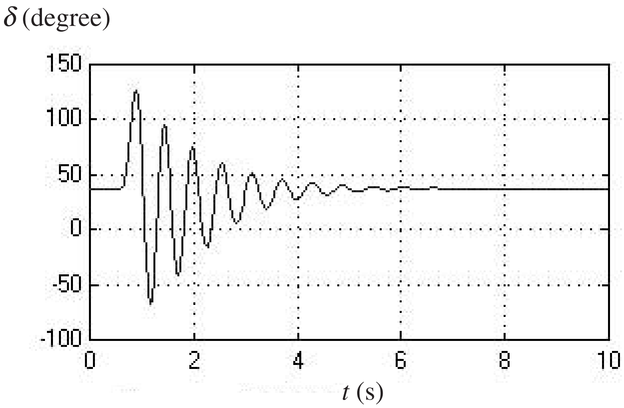

Fig. 14 *The deviation of the rotor angle.*

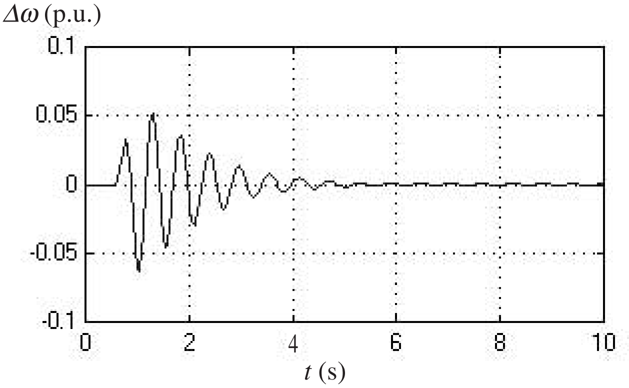

Fig. 15 *The deviation of the angular speed.*

of the terminal voltage of the synchronous machine. Fig. 13 represents the deviation of the electrical power. Figs 14 and 15 represent the deviation of the rotor angle and the deviation of angular speed, respectively.

Conclusion

SIMULINK uses the groups of block diagrams to represent dynamic systems. In this work, a model for simulation of the synchronous machine is constructed by using properly selected sub-blocks. For transient analysis, the synchronous machine-infinitive bus system is investigated using SIMULINK. As shown in this study, SIMULINK provides a powerful tool for investigating power systems including synchronous machines for research and educational purposes.

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