

# A Power System Dynamic Simulation Program Using MATLAB/ Simulink

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**Abstract:** The paper illustrates a procedure to develop a dynamic simulation program for a single machine infinite bus (SMIB) test system using MATLAB/Simulink software. The program is useful to demonstrate various operational and stability challenges in power system operations. The method can be extended to make a program to simulate network having multiple synchronous machines, asynchronous machines, FACTS devices, dynamic load etc.

**Keywords:** Power system dynamics, modelling, Synchronous machines, MATLAB, Simulink

## I. INTRODUCTION

Modelling and simulation studies are an integral part of power system analysis. They are used in the electricity related industry from the early days of digital computers. They are used to study the operation and stability of the system, controllers design and testing, operator training etc.

This paper deals with programming of a single machine infinite bus (SMIB) test system using MATLAB/ Simulink software and intended for a complete beginner in the field of power system analysis. A basic methodology for developing a simulation program is discussed without detailing the theory behind the model. The program can be modified to include multiple synchronous machines, asynchronous machines, FACTS devices, dynamic load etc.

The paper is divided into four sections. Following the introductory section, the Section II deals with the modelling aspects of a power system and lists key equations for dynamic model of a synchronous machine. The Section III explains the procedure for translating the dynamic model into a Simulink model. Results of an SMIB test system simulation are discussed in Part IV and several suggestions for possible future work are detailed.

## II. DYNAMIC MODELLING OF POWER SYSTEM

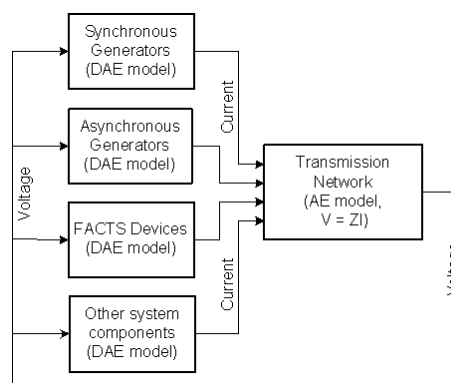


Fig. 1 Overview of power system simulation program

A model of a power system is an integration of several dynamic models such as synchronous generators, asynchronous generators, load, FACTS devices, etc. Fig. 1 shows a top level view of the model, where various dynamic models are connected to a network model. The output of the network model is fed back to the dynamic models making it a closed loop system. The network model consists of all transmission network components except the components modeled separately. It is represented using an algebraic equation  $V = Z I$  where  $V$  is a vector of bus voltage,  $I$  is a

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vector of injected current at each bus where the dynamic components are connected and  $Z$  is a matrix representing the impedance of transmission line and other components not modelled separately. (In some system studies, a more detailed model of transmission network using differential equations is used.) The output of the network block, bus voltage, is fed to the dynamic models. The dynamic models consist of differential and algebraic equations (DAE), and the outputs are injected current at corresponding buses.

An SMIB simulation presented in this paper contains only a synchronous machine model block and a network model block. The modelling of synchronous generator is a subject matter of many text books and literatures [1-3]. Models of varying degree of complexity are reported. Choice of a model is made depending on the type of phenomena being studied and available computational resource. The DAE equations for a transient model of synchronous machine are explained here. Theory behind these equations is not explained as it is beyond scope of this paper.

### A. Synchronous machine model

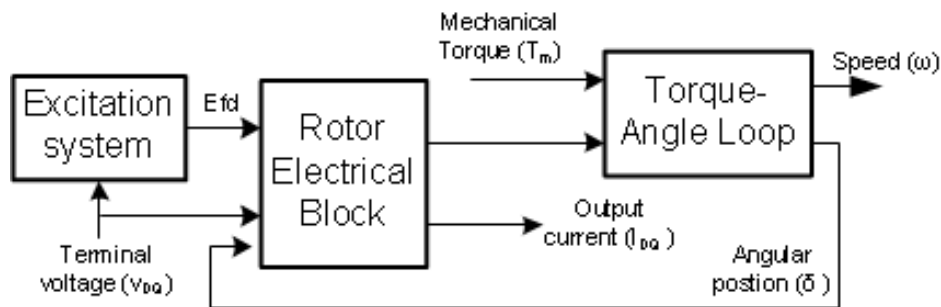


Fig. 2 Block diagram representation of synchronous machine model

A synchronous generator generally has two inputs, a torque input from a turbine coupled to its rotor and an excitation current to field winding in its rotor. The excitation current produces magnetic poles in the rotor. When the mechanical torque from turbine forces the rotor to rotate, a rotating magnet field will be created in the air gap which cuts the stationary coils in the stator, and induces a voltage in the stator winding. Hence the mechanical torque supplied by a turbine is converted to electrical torque through the flux linkage and transmitted to grid as voltage and current.

Fig. 2 shows an internal block diagram representation of a synchronous machine model. It consists of three blocks, namely torque-angle loop, rotor electrical block, and excitation system block.

The torque angle loop represents turbine and generator mechanical system. Inputs to this block are mechanical and electrical torques, and outputs are rotating speed and rotor position. If mechanical torque and electrical torque are balanced, the rotor will rotate at a constant speed called synchronous speed. A change in either of the torques will cause the speed to change. Another output of the block is the rotor position. Consider any fixed point in the rotor. For an outside observer, the point will rotate in a circle and hence the rotor position will change from 0 to 360 degree. However, if the observer is rotating at the synchronous speed, the point will look stationary. Now the rotor position represents the relative angle between the observer and the point. When an imbalance occurs in the torques, the observer will notice a change in the speed and the rotor position. In the dynamic synchronous machine model, parameters are resolved into the rotating observers frame, generally called rotating reference frame using Parks's transformation [2]. This paper does not describe details of this transformation. Readers are advised to refer relevant literature to understand this concept.

The rotor electrical block represents flux dynamics in the machine windings. The excitation system block compares terminal voltage magnitude with a reference voltage, and outputs field voltage. There are two inputs for the synchronous machine model. One of them is the mechanical torque which is assumed to be constant during the course of simulation. The second one is terminal bus voltage  $v_t$  obtained from the network block. The output of the model is current  $i_t$  which is fed to the network block.

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DAE equations corresponding to the individual blocks are listed below. This paper does not cover details of these equation as it is beyond its scope. [1-2] provides detailed analysis of these equations.

### 1) Equations for rotor electrical block

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (1)$$

$$\frac{d\omega_i}{dt} = \frac{\omega_s}{2H_i} [-D_i(\omega_i - \omega_s) + T_{mi} - T_{ei}] \quad (2)$$

for  $i = 1, 2, 3 \dots m$ , where,

$m$ : total number of generators. In the SMIB system  $m = 1$

$\delta_i$ : rotor angle of  $i^{\text{th}}$  generator

$\omega_i$ : Speed of  $i^{\text{th}}$  generator

$\omega_s$ : Synchronous speed of generator

$H_i$ : Inertia of  $i^{\text{th}}$  generator

$D_i$ : Damping coefficient of  $i^{\text{th}}$  generator

$T_{mi}$ : mechanical input torque of  $i^{\text{th}}$  generator

$T_{ei}$ : electrical output torque of  $i^{\text{th}}$  generator

### 2) Equations for rotor electrical block

One of the inputs to this block is the terminal voltage,  $\mathbf{V}_t$ . It is a complex number which can be written as,  $\mathbf{V}_t = \mathbf{v}_{Qi} + j\mathbf{v}_{Di}$ . This voltage is transformed to a synchronously rotating reference frame as  $\mathbf{v}_{qi} + j\mathbf{v}_{di}$  using (3).

$$(v_{qi} + jv_{di}) = v_{DQi} e^{-j\delta_i} = (v_{Qi} + jv_{Di}) e^{-j\delta_i} \quad (3)$$

$$\frac{dE'_{qi}}{dt} = \frac{1}{T'_{di0}} [-E'_{qi} + (x_{di} - x'_{di})i_d + E_{fdi}] \quad (4)$$

$$\frac{dE'_{di}}{dt} = \frac{1}{T'_{qi0}} [-E'_{di} - (x_{qi} - x'_{qi})i_{qi}] \quad (5)$$

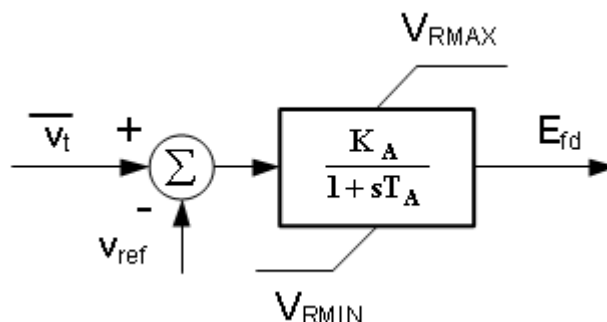
$$\frac{dE'_{dci}}{dt} = \frac{1}{T_{ci}} [-E'_{dci} - (x'_{qi} - x'_{di})i_{qi}] \quad (6)$$

Equation (6) represents a dummy rotor coil used to handle transient saliency. A detailed discussion on treating saliency is available in [1].

$$(i_{qi} + ji_{di}) = \frac{1}{(R_{ai} + jx'_{di})} [E'_{qi} + j(E'_{di} + E'_{dci}) - (v_{qi} + jv_{di})] \quad (7)$$

$$T_{ei} = E'_{di}i_{di} + E'_{qi}i_{qi} + (x'_{di} - x'_{qi})i_{di}i_{qi} \quad (8)$$

$$i_{DQi} = (i_{Qi} + ji_{Di}) = (i_{qi} + ji_{di})e^{j\delta_i} \quad (9)$$



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Fig. 3 Block diagram representation of excitation system model

- $v_{qdi} = v_{qi} + jv_{di}$ : voltage in Park's reference frame
- $v_{QDi} = v_{Qi} + jv_{Di}$ : voltage in Kron's reference frame
- $i_{QDi} = i_{Qi} + ji_{Di}$ : current in Kron's reference frame
- $E'_{qi}$ : transient emf due to field flux linkage
- $E'_{qdi}$ : transient emf due to flux linkage in q-axis damper coil
- $E'_{dci}$ : transient emf due to flux linkage in dummy rotor coil
- $i_{di}$ : d-axis component of stator current
- $i_{qi}$ : q-axis component of stator current
- $x_{di}, x'_{di}$ : synchronous and transient reactance along d-axis, respectively
- $x_{qi}, x'_{qi}$ : synchronous and transient reactance along q-axis, respectively
- $T'_{qi}, T'_{di}, T'_{ci}$ : open circuit transient time constant along q-axis, d-axis and dummy coil, respectively

### 3) Excitation system block

The block diagram representation of a static excitation system is shown in Fig. 3 [1].  $V_t$  and  $E_{FD}$  are input, the magnitude of terminal voltage and output, the field voltage, respectively. The regulator transfer function has a single time constant  $T_A$  and positive gain  $K_A$ .

## III. DEVELOPMENT OF A SIMULINK MODEL

This section explains steps involved in building a simulink model to simulate an SMIB test system. The model described in the previous section contains several differential equations. Hence to start with, section \ref{sec\_sec1} describes how to program a simple first order differential equation using the Simulink. In section \ref{sec\_sec2}, programming of the torque angle loop block is explained.

### A. Simulating a first order differential equation using Simulink

Let us take a first order transfer function given by (10),

$$\frac{y}{x} = \frac{1}{1 + sT_a} \tag{10}$$

It can be written as

$$y + T_a s y = x \tag{11}$$

$$\frac{dy}{dt} = \dot{y} = \frac{1}{T_a} (x - y) \tag{12}$$

$$y = \int \dot{y} + y(0) \tag{13}$$

where  $y(0)$  is an initial value of the state  $y$ . The initial value indicates the value of a state under steady state, i.e.  $dy/dt=0$ . From (12),  $y(0) = x$ .

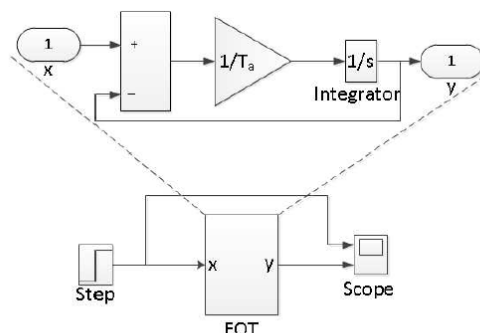


Fig. 4: Simulink representation of a first order transfer function

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Fig. 4 shows Simulink model for the transfer function in (10). The initial value  $\mathbf{y}(0)$  is specified as a parameter in the integrator block.

The power system model presented above consists of non-linear equations which call for a numerical solution. It is assumed that, the system is at a stable equilibrium point (SEP) at time  $t=0$  and a disturbance happens at  $t>=0$ . To start the simulation, it is necessary to calculate the initial value of all machine states,  $\mathbf{x}0$  at time  $t=0$ .

## B. Calculating initial conditions for the SMIB model

The primary step in initializing the model is to obtain a power flow solution of the network. The power flow solution gives real and reactive power output of generators  $\mathbf{P}_g$  and  $\mathbf{Q}_g$ , and terminal voltage magnitude and angle  $\mathbf{V}_t$  and  $\mathbf{\theta}_t$  at buses. At SEP, the change in value of the states with time is zero which means, the  $\mathbf{d/dt}$  term in all differential equations can be set to zero and the initial value of states can be deduced. A step by step procedure for initial value computation for the synchronous machine specific to this work is listed below. A more detailed explanation is available in [2]. The subscript  $\mathbf{0}$  in the following equations indicates initial value or steady state value of the state variables.

- Run a power flow model and obtain  $P_g, Q_g, V_{g0}$  and  $\theta_{g0}$  for the generator bus. For an SMIB test system, power flow solution can be calculated using a simple calculation. For a large network, power flow programs are used to obtain this value.
- Compute output current,  $I_{g0} \angle \phi_0 = \frac{P_g - jQ_g}{V_{g0} \angle \theta_{g0}}$
- Compute  $E_{q0}$  and  $\delta_0$  from,  $E_{q0} \angle \delta_0 = V_{g0} \angle \theta_{g0} + (R_a + jx_q) I_{g0} \angle \phi_0$
- Compute
 
$$i_{d0} = -I_{g0} \sin(\delta_0 - \phi_0)$$

$$i_{q0} = I_{g0} \cos(\delta_0 - \phi_0)$$

$$v_{d0} = -V_{g0} \sin(\delta_0 - \phi_0)$$

$$v_{q0} = V_{g0} \cos(\delta_0 - \phi_0)$$
- Compute
 
$$E_{fd0} = E_{q0} - (x_d - x_q) i_{d0}$$

$$E'_{q0} = E_{fd0} + (x_d - x'_d) i_{d0}$$

$$E'_{d0} = - (x_q - x'_q) i_{q0}$$

$$T_{e0} = E'_{q0} i_{q0} + E'_{d0} i_{d0} + (x'_d - x'_q) i_{d0} i_{q0} = T_{m0}$$

The above steps will initialize the rotor electrical block.

## C. Simulating torque and loop block using Simulink

The torque angle loop block contains two first order differential equations (1, 2). At steady state, both  $\mathbf{d\delta/dt}$  and  $\mathbf{d\omega/dt}$  are equal to zero and the initial value of  $\mathbf{\omega}$  and  $\mathbf{T_m}$  can be computed. Following the method described in Section III-A, a Simulink model for torque angle loop can be built as shown in Fig.5.

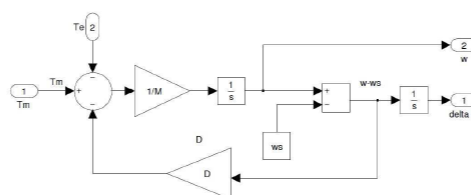


Fig. 5: Implementation of Torque-Angle loop

Similarly, differential equations corresponding to rotor electrical blocks can be programmed as shown in Fig. 6. The static excitation system block is essentially a first order transfer function and is programmed similar to Fig. 4.

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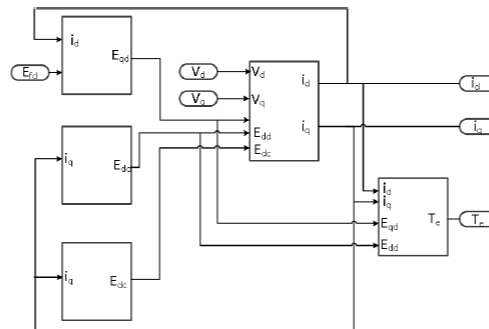


Fig. 6: Implementation of rotor electrical block shown in Fig. 2

## IV. SIMULATION RESULTS

An SMIB system shown in Fig. 7 is used to demonstrate the programming. In the test system a synchronous machine is connected to a grid through a transformer and a double circuit transmission line [2]. The grid is represented using impedance connected to an infinite bus. The infinite bus means that the bus has fixed voltage and frequency. The system can be used to study the interaction of the generator with the grid.

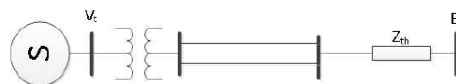


Fig. 7: Simulink representation of a first order transfer function

The parameters of the system on a 100MVA system bases are given below.

Generator:  $R_a = 0.00327$ ,  $x_d = 1.7572$ ,  $x_q = 1.5845$ ,  $x'_d = 0.4245$ ,  $x'_q = 1.04$ ,  $T'_{d0} = 6.66$ ,  $T'_{q0} = 0.44$ ,  $H = 3.542$ ,  $f_B = 50\text{Hz}$ ,  $D=0$ .

Transformer:  $R_t = 0.0$ ,  $x_t = 0.1364$

Transmission line:(per circuit)  $R_l = 0.08593$ ,  $x_l = 0.8125$ ,  $B_c = 0.1184$ ,  $Z_{th} = j0.13636$

Excitation system:  $K_A = 400$ ,  $T_A = 0.025$

### A. Steady state operating condition of the SMIB test system

Under steady state the active and reactive power output of the machine are assumed as  $P_t = 0.6$ ,  $Q_t = 0.0228$ . For an infinite bus voltage  $E_B = 1.0$ , the terminal voltage of the generator is calculated as  $V_t = 1.05 < 21.83$ . Using the method described in the Section III-B following initial values are computed.  $\delta_0 = 61.5$  degree,  $E'_{q0} = 0.9704$ ,  $E'_{d0} = -0.2314$ ,  $i_{d0} = -0.3825$ ,  $i_{q0} = 0.4251$ ,  $E_{fd0} = 1.4802$ ,  $T_{m0} = 0.6011$ .

### B. Response of the SMIB system to step change in infinite bus voltage

A step change in the infinite voltage is applied at time  $t=1$  which is plotted in 8(a). The dynamic response of  $V_t$ ,  $P_g$ ,  $Q_g$ ,  $T_e$ ,  $\delta$  are plotted in Fig. 8(b) to Fig. 8(f). The variation in  $\delta$  following the disturbance is with respect to the rotating reference frame.

### C. Suggestions for further work

The simulation set up described in this paper can be used to analyze the response of the machine under various system disturbances. Few examples are, three phase fault, transmission line trip, change in excitation reference voltage, change in input mechanical torque. A governor model can be added to the program to study the frequency response of the synchronous machine.

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A state space model of the system can be obtained using the *linmod* command and the eigenvalues can be computed using *eig* commands available in MATLAB. It is possible to explore possibility of designing a power system stabilizer for this system.

The concept explained in this paper can be extended to make a multi-machine system simulation with asynchronous generators and FACTS devices.

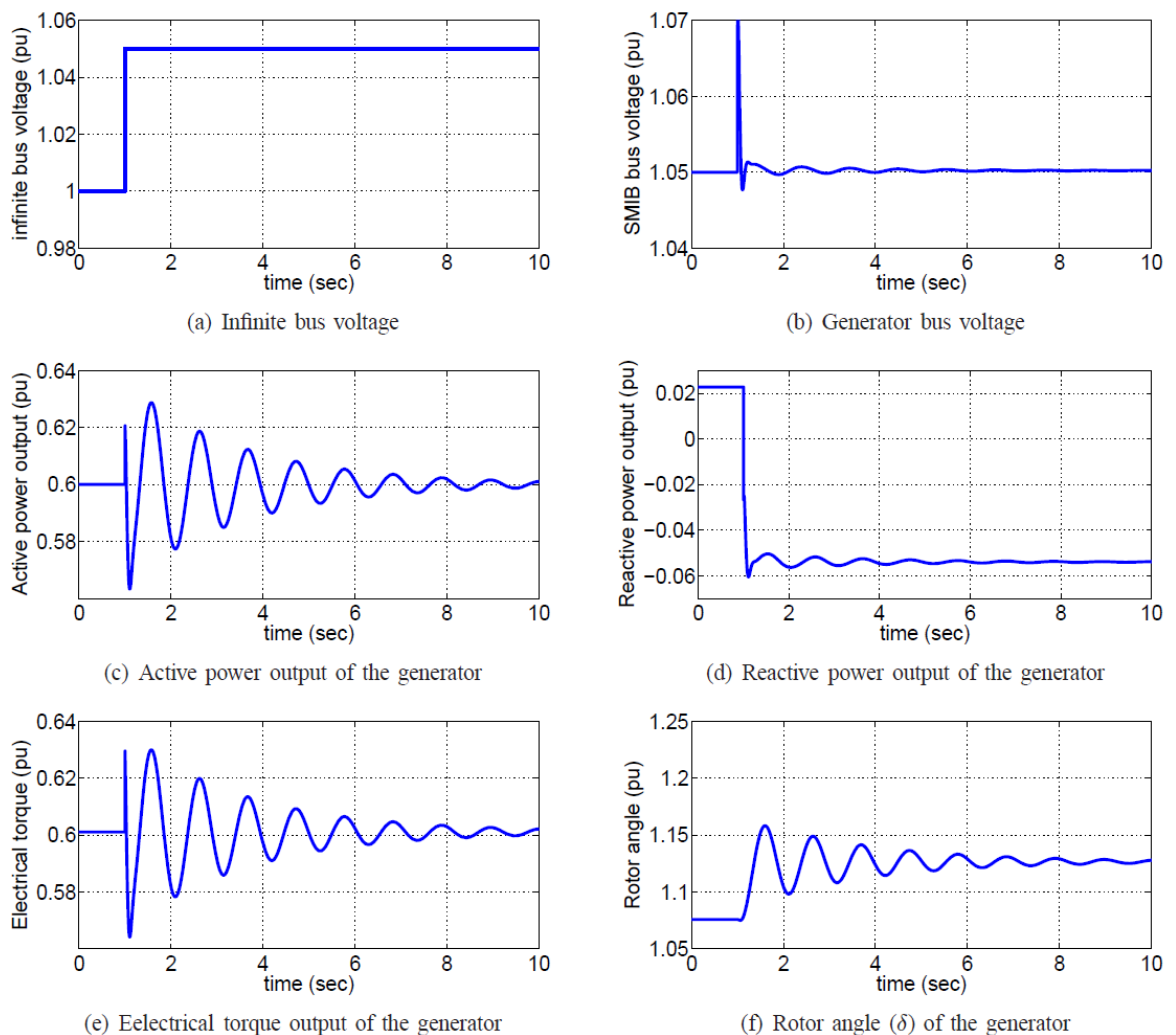


Fig. 8: Response of SMIB system to step change in infinite bus voltage

## V. CONCLUSION

A programming approach for simulating a power system using MATLAB/ Simulink is discussed in this paper. The concept is explained using a SMIB test system simulation. The dynamic response of the test system to a disturbance in the grid is presented to further illustrate the method and several suggestions for further development are listed.

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## BIOGRAPHY

**Linash P. Kunjumammed** received the B. Tech degree from Mahatma Gandhi University, India, the M. S. degree from the Indian Institute of Technology Madras, India, and the Ph.D. degree from the Imperial College London, London, U.K., in 2002, 2006, and 2012, respectively. From 2006 to 2008, he was with TVS Motor Company Ltd., Hosur, India. Currently he is a post doctoral fellow in the department of electrical and electronic engineering, Imperial College London.

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