



TRANSIENT STABILITY SIMULATION OF MULTI-MACHINE POWER SYSTEMS USING SIMULINK

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Abstract: This paper describes a generalized dynamic model of multi-machine power systems for transient stability analysis and its computer simulation using MATLAB/SIMULINK. The generalized model of the power systems can be used for teaching the power system transient phenomena, as well as for research works particularly to improve generator controllers with advanced technologies. Constructional details of various sub-models for the whole power systems are given and their implementation in SIMULINK environment is outlined. The developed simulation model is tested on 3-machine 9-bus power system and 10-machine 39-bus New England power system under different large disturbances. For the studied cases, the critical clearing times (CCT) are calculated and the simulation results are presented and discussed. Nonlinear time-domain simulation results obtained from several case studies validate the effectiveness of proposed model for transient stability analysis. The proposed dynamic model has been employed to support and develop power engineering education at both the undergraduate and graduate levels. Likewise, for academic and educational use, all component sub-models are transparent and can simply be modified or extended.

Keywords: Transient stability, multi-machine power systems, MATLAB/SIMULINK, power system modeling, power system simulation..

1. Introduction

The term "transient stability," in the power system stability studies, mostly denotes the capacity of synchronous machines for remaining in synchronism for the short period of time subsequent to large disturbances, including a fault on transmission facilities, loss of a large load and sudden loss of generation. The system response to such disturbances contains generator rotor angles' large excursions power flows, bus voltages and other system variables. It is worth mentioning that, while steady-state stability is a function only of operating conditions, transient stability is a function of both the operating conditions and the disturbances [1]. This entangles the transient stability analysis noticeably. System nonlinearities, in large disturbances, have a significant role.

To control transient stability or instability subsequent to a large disturbance, or a number of disturbances, time-domain simulation analysis is commonly used to solve the nonlinear equations set explaining the dynamic behavior of system. In that case, conclusion pertaining to stability or instability can be obtained from an inspection of the solution [2-3]. Fault clearing time (FCT) and critical clearing time (CCT) are significant parameters so as to preserve power systems transient stability. The FCT is the time upon which the fault is cleared following the fault occurrence, while the CCT is the fault clearing time

upon which the system is at the critically stable level. If the actual fault clearing time in a system is below the CCT level, the system will be stable [4].

Simulation programs for power system stability analysis can be divided into two classes of tools: commercial software packages and education/research-aimed software packages. Various commercial software packages, such as Power System Simulator for Engineering (PSS/E), Power System Simulator (Simpow), DigSilent, EuroStag, NEPLAN and PowerWorld, are on sale. These programs allow users to access comprehensive component/system, models and computationally efficient algorithms for the analysis. Nevertheless, these programs are not appropriate for educational and research fields because they generally do not provide modification or incorporation of novel component models and algorithms. In education and research fields, flexibility and potential for simple prototyping are much more crucial aspects than its computational efficiency.

This paper discusses the use of SIMULINK software of MATLAB in the dynamic modelling of multi-machine power systems for transient stability simulation. SIMULINK is a software package developed by MathWorks Inc., which is one of the most widely used software in academia and industry for modeling, analysis and simulating dynamical systems. It can be used for modeling linear and nonlinear systems, either in continuous time frame or sampled time frame of even a hybrid of the two. It provides a very easy drag-drop type graphical user

interface to build the models in block diagram form. It has many built-in block library components that you can use to model complex systems. If these built-in models are not enough for you, SIMULINK allows you to have user defined blocks as well. Over the last decade, the topic of power system simulation in MATLAB/SIMULINK has been provided in [5-12]. The use of the MATLAB/SIMULINK for the enhancement of power system component can allow users to take full advantage of dealing with control blocks and power system elements, corroborating new component through comparison of the simulation results for numerous events, and understanding of the basic concepts of power system modeling and simulation.

In this paper, we have developed SIMULINK-based generalized dynamic model and an efficient approach so as to examine the transient stability performance of practical power systems, with SIMULINK as a tool. The aim of the generalized dynamic model is to provide an environment within which students can quickly get started and provides enough modeling flexibility to allow modification or addition of new generator, load, and control system models. Whereas ease of use is mostly important for coursework, the modeling flexibility is useful mostly for research applications. All component sub-models are transparent and can easily be modified or extended. Emphasis has been given to keeping the component sub-models transparent and simple. All component sub-models are designed for use by undergraduate and graduate students in the learning of power system transient stability and for rapid testing of research ideas. The proposed model for transient stability simulation has been applied to different examples of multi-machine power systems such as IEEE 9-bus and IEEE 39-bus power systems. The nonlinear simulation results have been carried out to assess the effectiveness of the developed transient stability simulation model under various large disturbances. We hope that this attempt will add some more practical information in this important and unexhausted domain.

2. Multi-machine Power System Model Constructed Using SIMULINK

Regarding transient electromechanical phenomena analysis of a power system, power flow algebraic equations for the transmission network and for the stator windings of the synchronous machines, together with the differential equations for the rotor of the synchronous machines are commonly used. For that reason, the power system mathematical model can be formulated by a set of differential and algebraic equations (DAEs) [13]. In this study, the flux-decay model with static exciter is employed to discuss the synchronous machines.

The whole system is given with regard to SIMULINK blocks in three main single sub-models. One of the most significant characteristics of a model in SIMULINK is its remarkable interactive ability. In

other words, it allows the display of a signal at any point readily available; all one has to do is to add a Scope block or, alternatively, an output port. What's more, giving a feedback signal is as easy as drawing a line. A parameter within any block can be regulated from MATLAB command line or through an *m-file* program. This is a predominantly helpful for multi-machine power system transient stability study because the power system configurations change before, during and after a fault. Loading conditions and control measures can be employed correspondingly.

2.1. Differential Equations

The differential equations of the machine and exciter for the m machine, n bus system are expressed as follows [13]:

$$\frac{d\delta_i}{dt} = \omega_s \omega_i - 1 \quad i = 1, 2, \dots, m \quad (1)$$

$$\frac{d\omega_i}{dt} = \frac{P_{mi}}{M_i} - \frac{P_{ei}}{M_i} - \frac{D_i(\omega_i - 1)}{M_i} \quad i = 1, 2, \dots, m \quad (2)$$

$$\frac{dE'_{qi}}{dt} = -\frac{E'_{qi}}{T'_{doi}} - \frac{(x'_{di} - x'_{di})i_{di}}{T'_{doi}} + \frac{E_{fdi}}{T'_{doi}} \quad i = 1, 2, \dots, m \quad (3)$$

$$\frac{dE_{fdi}}{dt} = -\frac{E_{fdi}}{T_{Ai}} + \frac{K_{Ai}}{T_{Ai}} V_{refi} - V_i \quad i = 1, 2, \dots, m \quad (4)$$

2.2. Stator Algebraic Equations

The stator algebraic equations describe the electrical variables pertaining to the stator windings. The stator algebraic equations are expressed as

$$V_i \sin(\delta_i - \theta_i) - x_{qi} i_{qi} = 0 \quad i = 1, 2, \dots, m \quad (5)$$

$$E'_{qi} - V_i \cos(\delta_i - \theta_i) - x'_{di} i_{di} = 0 \quad i = 1, 2, \dots, m \quad (6)$$

2.3. Network Equations

The network equations can be expressed in power-balance or current-balance form. In this study, the current-balance form is employed and the loads are assumed to be of the constant impedance type. In power system with m generators, the nodal equation can be formulized as:

$$\begin{bmatrix} \bar{I}_1 \\ \vdots \\ \bar{I}_m \\ 0 \\ \vdots \\ 0 \end{bmatrix} = [\bar{Y}'] \begin{bmatrix} \bar{V}_1 \\ \vdots \\ \bar{V}_n \end{bmatrix} \quad (7)$$

$$\bar{I}_i = i_{di} + j i_{qi} e^{j \delta_i - \pi/2} \quad i = 1, 2, \dots, m \quad (8)$$

where $\bar{I}_1, \dots, \bar{I}_m$ are the complex injected generator currents at the generator buses. Assume that the modified \bar{Y}_{bus} represented as \bar{Y}' be divided as

$$[\bar{Y}'] = \begin{matrix} m & n-m \\ \bar{Y}_1 & \bar{Y}_2 \\ n-m & \bar{Y}_3 & \bar{Y}_4 \end{matrix} \quad (9)$$

Inasmuch as there are no injections at buses $m+1, \dots, n$, we can leave them out in order to obtain

$$\begin{bmatrix} \bar{I}_1 \\ \vdots \\ \bar{I}_m \end{bmatrix} = \begin{bmatrix} \bar{Y}_R \\ \vdots \\ \bar{V}_m \end{bmatrix} \quad (10)$$

where $\bar{Y}_R = \bar{Y}_1 - \bar{Y}_2 \bar{Y}_4^{-1} \bar{Y}_3$ is the desired reduced matrix. The reduced matrices for every network condition (before, during and after fault) are computed on account of the power system under study.

3. SIMULINK Models

The complete multi-machine power system embodied with regard to SIMULINK blocks in a single integral model by using Eqs. (1)-(10) for transient stability study. The complete system consists of three main sub-models: differential equations sub-model, stator algebraic equations sub-model, and network equations sub-model. The SIMULINK-based general sub-models for computing of differential equations and stator algebraic equations are modeled and are given for all generators in Figure 1 and Figure 2 respectively. We can see in the complete sub-model of Figure 1 that **Scope 1** and **Scope 2** display the individual generator angles and the angular velocities of the all machines, respectively. In Figure 2, **Scope 5** and **Scope 6** monitor electrical power outputs and machine terminal voltages responses respectively, for all generators. It is worth mentioning that in Figure 1 and Figure 2; δ , ω , M , D , E'_q , E'_{fd} , K_A , T_A , V , V_{ref} , P_m and P_e are vector signals having as many rows as the number of generators.

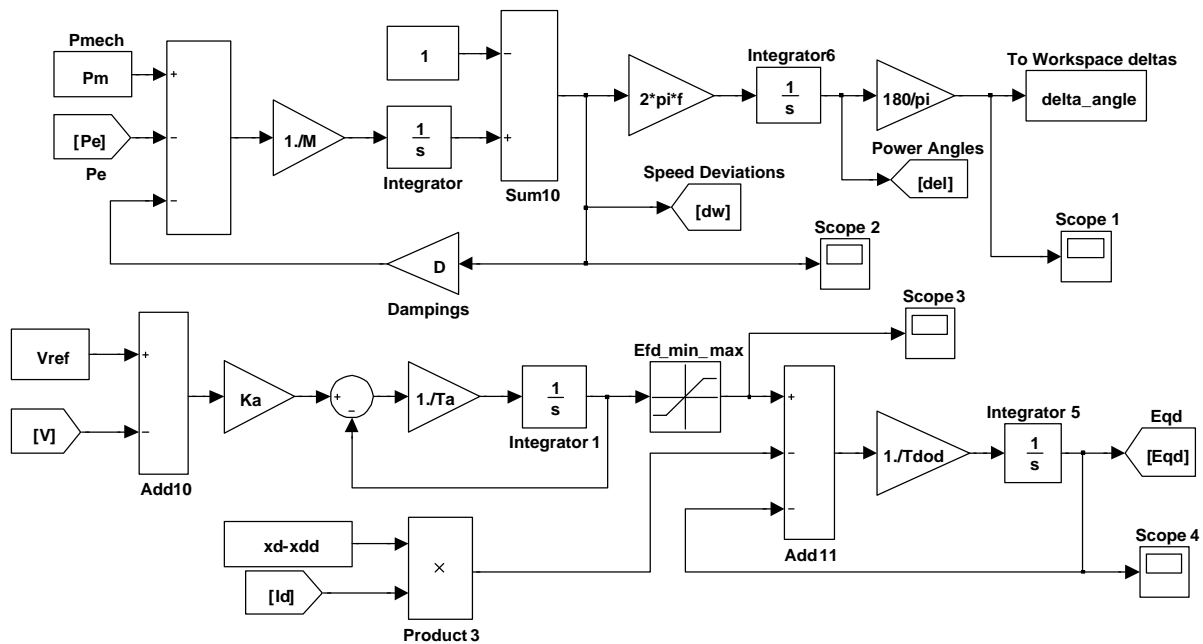


Figure 1. Differential equations sub-model for transient stability simulation

Figure 3 illustrates the complete block diagram of network equations for all generators in SIMULINK environment. The **SUBSYSTEM** in Figure 3 is expressed to calculate the value of electrical current outputs for different generators and internal view of the **SUBSYSTEM** is given in Figure 4. In Figure 4 it includes a block to specify network admittance matrices required for numerous conditions of the power transmission network: before, during and after a specified fault. These admittance matrices are calculated by using an associated MATLAB program prior to starting transient stability simulations of multi-machine power systems, and fault location can be randomly specified.

Likewise, prior to starting transient stability simulations, it is mandatory to specify the initial conditions of a number of quantities for all machines, consequently, a power flow calculation is performed by using the same associated MATLAB program, in which the pre-fault and the fault clearing time are specified. The main SIMULINK-based sub-models are simply modified for multi-machine power systems with different number of generators and also different network configurations. In addition, the generalized dynamic model of multi-machine power systems in SIMULINK environment also facilitates the choice of simulation parameters, including start and stop times, types of solver, step sizes, tolerance and output options.

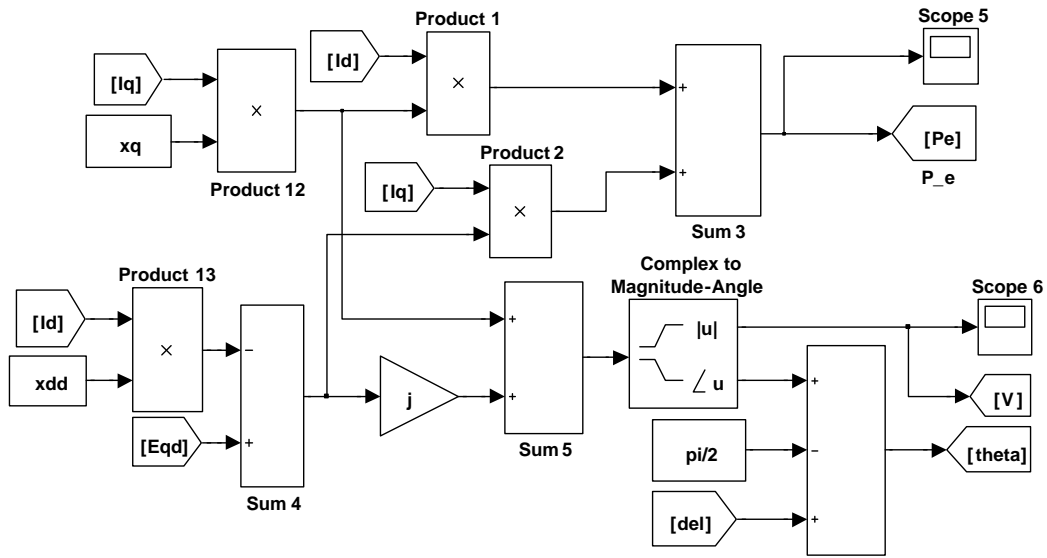


Figure 2. Stator algebraic equations sub-model for transient stability simulation

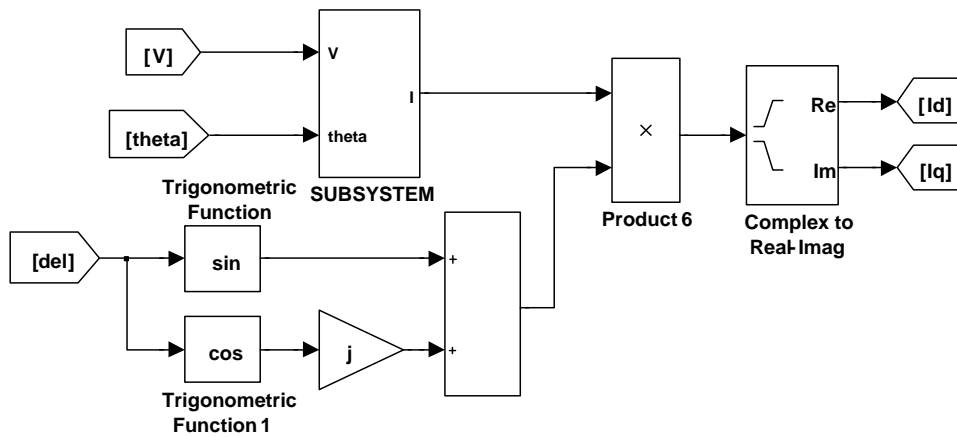


Figure 3. Network equations sub-model for transient stability simulation

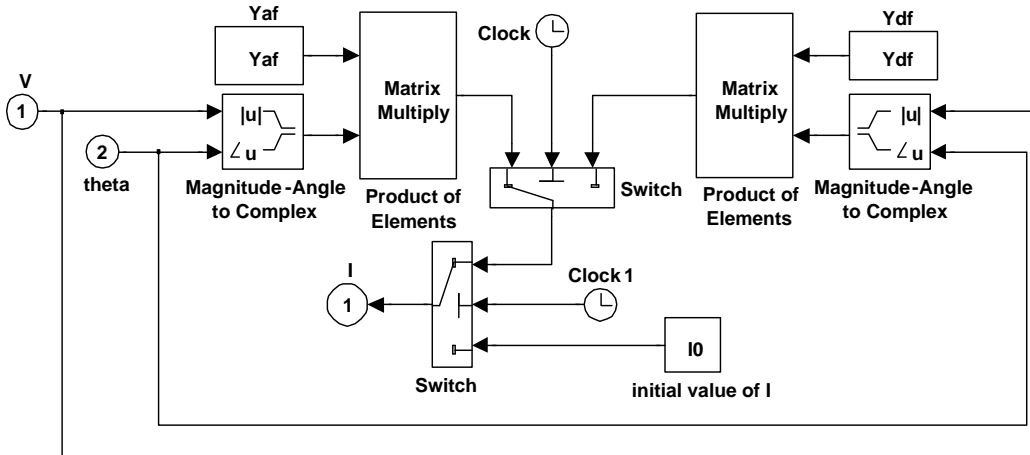


Figure 4. Internal view of the *SUBSYSTEM*.

4. Results of Transient Stability Simulations and Discussions

In this section, we illustrate the DAE model discussed in the previous section and to validate SIMULINK-based generalized model, the simulations are carried out on a 3-machine 9-bus and 10-machine 39-bus New England power systems. To assess the effectiveness of the proposed dynamic model, nonlinear time-domain simulation studies are implemented on different severe fault conditions. In transient stability simulation of multi-machine power systems, Runge-Kutta 4 technique is used for

numerical integration of the differential equations and step of integration is chosen as 0.005 s. All calculations were done on a personal computer with 2.10 GHz Intel Core Processor and 2.00 GB of RAM running MATLAB/SIMULINK 7.11.0.

4.1. Illustrative System example 1: Nine-bus three-machine power system

In this example, we have considered the popular Western System Coordinated Council (WSCC) 3-machine, 9-bus power system shown in Figure 5. This is also the system appearing in [13-14] and widely used in literature.

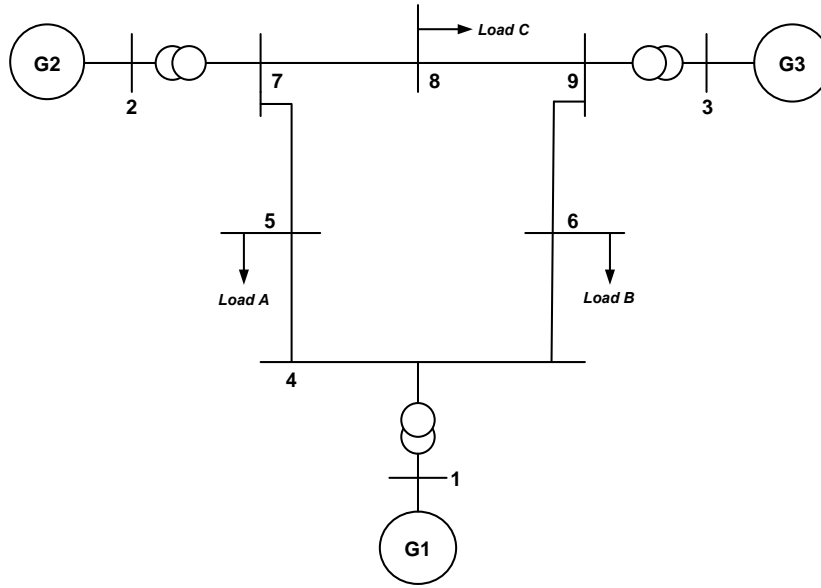


Figure 5. WSCC 3-generator 9-bus test system

We can see in the complete sub-model of Figure 1 that **Scope 1** display the values of the 3-machine angles in vector $\delta = \delta_1 \ \delta_2 \ \delta_3^T$ and **Scope 2** display the values of the 3-machine angular speeds in vector $\omega = \omega_1 \ \omega_2 \ \omega_3^T$. It is worth mentioning that the computation time for 3-machine 9-bus power system 3.28 s for 12 s of simulated real time. For time-domain simulations, different three-phase faults have been applied to demonstrate the effectiveness of the proposed dynamic model as follows:

The performance of the proposed dynamic model under transient conditions is substantiated by applying a three-phase fault at $t = 1$ s, on bus 9 at the end of line 8-9 is considered. The fault is then cleared by opening the line 8-9. The CCT for this scenario was found to be $t_{cr} = 0.192$ s by using a trial-and-error approach. The system responses are given for different values of fault clearing time (FCT).

Case (a): FCT < CCT, the fault occurs at 1 s and is cleared at 1.15 s (FCT = 0.15 s).

Case (b): FCT > CCT, the fault occurs at 1 s and is cleared at 1.20 s (FCT = 0.20 s).

Figures 6-7 show the difference angles ($\delta_{21} = \delta_2 - \delta_1$ and $\delta_{31} = \delta_3 - \delta_1$) and the relative rotor angular speed deviations ($\omega_{21} = \omega_2 - \omega_1$ and $\omega_{31} = \omega_3 - \omega_1$), respectively, for the system with FCT = 0.15 s. It is obvious from Figures 6-7 that the power system is stable in Case (a). Figures 8-9 show the system response for FCT = 0.20 s. From the results, we see that the system is unstable in Case (b) because all machines will lose synchronism.

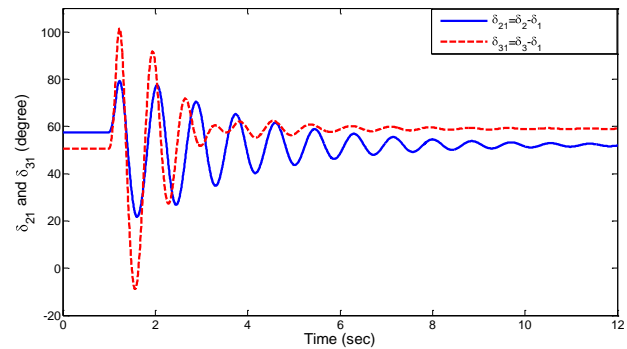


Figure 6. System response of $\delta_{21} = \delta_2 - \delta_1$ and $\delta_{31} = \delta_3 - \delta_1$ for FCT = 0.15 s

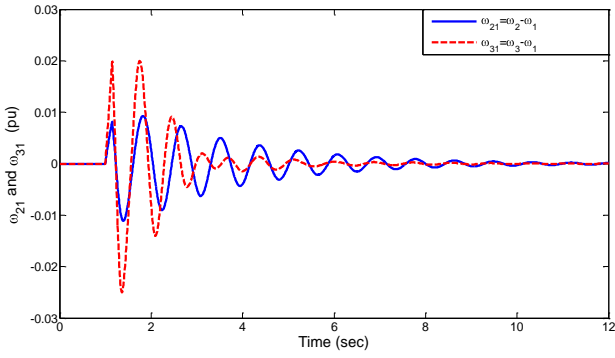


Figure 7. System response of $\omega_{21} = \omega_2 - \omega_1$ and $\omega_{31} = \omega_3 - \omega_1$ for FCT = 0.15 s

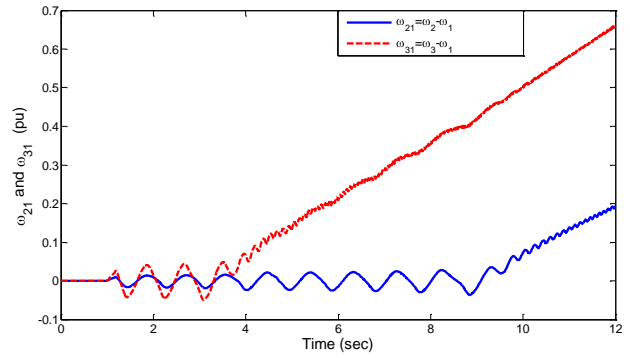


Figure 9. System response of $\omega_{21} = \omega_2 - \omega_1$ and $\omega_{31} = \omega_3 - \omega_1$ for FCT = 0.20 s

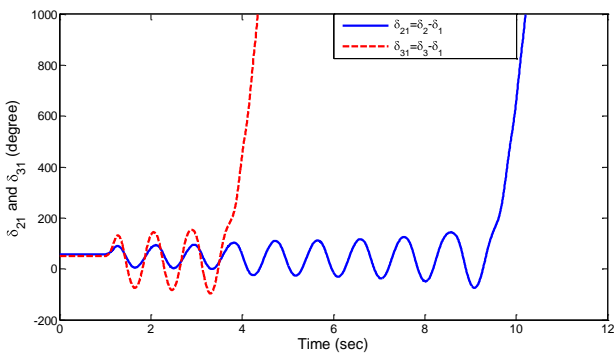


Figure 8. System response of $\delta_{21} = \delta_2 - \delta_1$ and $\delta_{31} = \delta_3 - \delta_1$ for FCT = 0.20 s

4.2. Illustrative system example 2: Thirty nine-bus ten-machine power system

In this part of the study, the 10-machine 39-bus New England power system shown in Figure 10 is considered further demonstrate the versatility of the suggested dynamic model. This is also the system appearing in [15-16] and widely used in the literature.

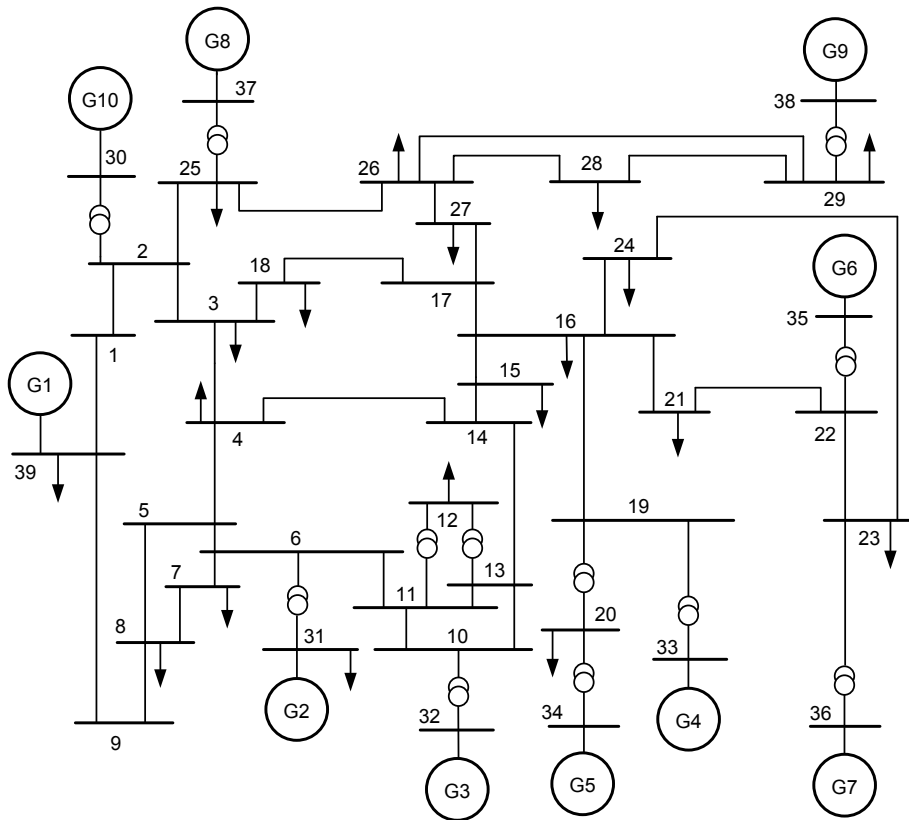


Figure 10. 10-machine, 39-bus New England test system

We can see in the complete sub-model of Figure 1 that **Scope 1** display the values of the 10-machine angles in vector $\delta = \delta_1 \ \delta_2 \ \delta_3 \ \delta_4 \ \delta_5 \ \delta_6 \ \delta_7 \ \delta_8 \ \delta_9 \ \delta_{10}^T$ and **Scope 2** display the values of the 10-machine angular speeds in vector $\omega = \omega_1 \ \omega_2 \ \omega_3 \ \omega_4 \ \omega_5 \ \omega_6 \ \omega_7 \ \omega_8 \ \omega_9 \ \omega_{10}^T$. The simulation was performed for 12 s and the computation time for this large power system 13.56 s. To assess the effectiveness of the proposed dynamic model, nonlinear time-domain simulation studies are implemented on different severe fault conditions. The following cases are taken into consideration:

A three-phase fault is applied on bus 29 (near generator 9) at the end of line 29-26 at $t = 1$ s. The fault cleared without line tripping and the original system is restored upon the clearance of the fault. The CCT for this scenario was found to be $t_{cr} = 0.125$ s by using a trial-and-error approach. The system responses are given for Case (a) and Case (b).

Case (a): $FCT < CCT$, the fault was initiated at 1 s and cleared at 1.10 s ($FCT = 0.10$ s).

Case (b): $FCT > CCT$, the fault was initiated at 1 s and cleared at 1.13 s ($FCT = 0.13$ s).

In this scenario, G_8 and G_9 are nearest generators to the fault location and therefore system responses are given for only these machines. For Case (a) and Case (b), the power system angle responses of G_8 and G_9 with respect to G_1 , ($\delta_{81} = \delta_8 - \delta_1$ and $\delta_{91} = \delta_9 - \delta_1$), are shown in Figure 11 and Figure 13, and the variations of the relative speed deviation of G_8 and G_9 with respect to G_1 , ($\omega_{81} = \omega_8 - \omega_1$ and $\omega_{91} = \omega_9 - \omega_1$), are shown in Figure 12 and Figure 14. In Figures 11-12, the FCT is set at 0.10 s while in Figures 13-14 the FCT is set at 0.13 s. Figure 11 shows that the relative rotor angles of the *Generator 8* and *Generator 9* oscillate and the system is said to be stable whereas Figure 13 shows that the relative rotor angle of the *Generator 9* go out of step after a fault is cleared and the systems becomes unstable.

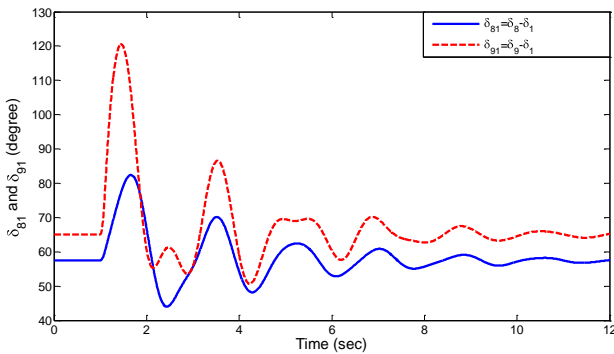


Figure 11. System response of $\delta_{81} = \delta_8 - \delta_1$ and $\delta_{91} = \delta_9 - \delta_1$ for FCT = 0.10 s

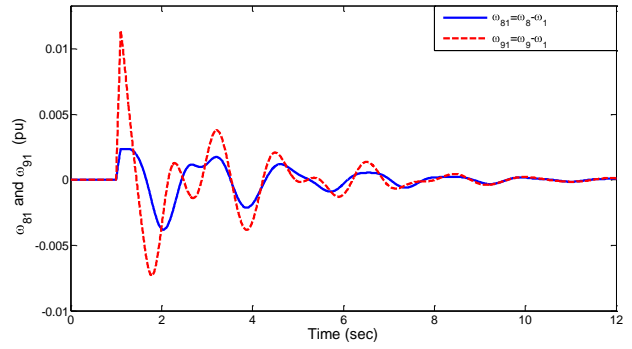


Figure 12. System response of $\omega_{81} = \omega_8 - \omega_1$ and $\omega_{91} = \omega_9 - \omega_1$ for FCT = 0.10 s

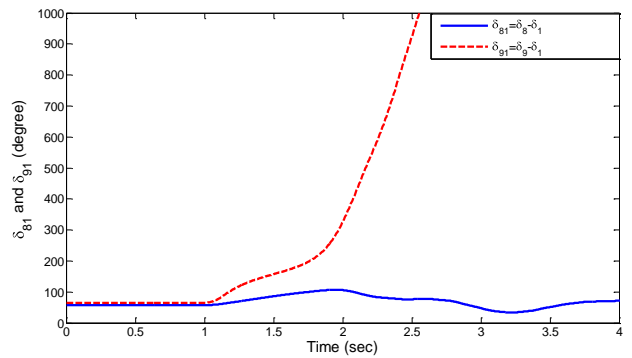


Figure 13. System response of $\delta_{81} = \delta_8 - \delta_1$ and $\delta_{91} = \delta_9 - \delta_1$ for FCT = 0.13 s

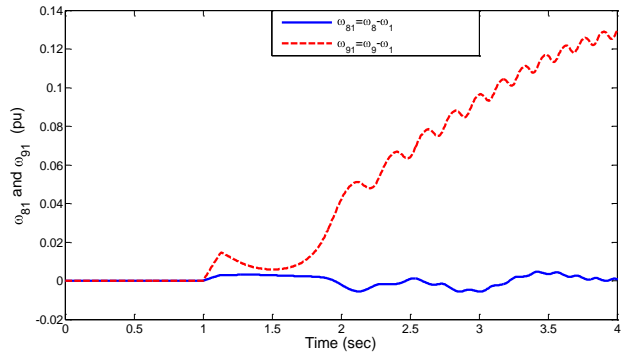


Figure 14. System response of $\omega_{81} = \omega_8 - \omega_1$ and $\omega_{91} = \omega_9 - \omega_1$ for FCT = 0.13 s

The effectiveness of the suggested dynamic model in multi-machine power systems is verified through the nonlinear simulation results. In addition, it can be deduced from Figures 6-9 and Figures 11-14 that the FCT setting is a significant factor to determine the power systems transient stability. If the FCT is set at a longer time than the CCT of the faulted line, the system will be unstable; otherwise the system will be stable.

5. Conclusion

SIMULINK is a powerful software package for the study of dynamic and nonlinear systems. Using SIMULINK, the simulation model can be built up

systematically starting from simple sub-models. A self-sufficient generalized dynamic model for transient stability simulation of multi-machine power systems has been given with full details, which can work as a basic structure for advanced and detailed studies. The models built in this way are easy to be understood by students and engineers. The proposed dynamic model has an open structure and all sub-models can be modified or extended using various SIMULINK constructs. The efficiency of the proposed MATLAB/SIMULINK-based transient simulation model has been tested and demonstrated through the transient stability simulations under various disturbance conditions and different fault clearing times, by using the three and ten machine study systems. Several cases have been also carried out to determine the effect of the clearing time of a fault on the transient stability of multi-machine power systems.

The proposed dynamic model shows to be a powerful didactic and research tool, able to provide important information about various aspects of transient stability phenomena. This educational model is also used for illustration purposes during lectures, as well as by students preparing personal assignments and design projects. The authors believe that SIMULINK will soon become an indispensable tool for the teaching and research of power systems.

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control technology and the applications of heuristic optimization to power system control.



and alternative power sources, and applications of AI techniques in power systems.

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