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Transient Stability Analysis Of Power Systems With Energy Storage

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***Abstract*— This paper presented the analysis of transient stability of power systems with distributed generation. Power systems can effectively damp power system oscillations through appropriate management of real or reactive power. In this work, a model of three machines IEEE 9-Bus system was developed with and without energy storage. Power System Analysis Toolbox (PSAT) model was used for the system during pre-fault, fault and post-fault conditions and the stability of the system was observed for different fault clearing times. From the phase angle characteristics results obtained, it was observed that the relative swing between the generator phase angle is low when the fault clearing time is low. When the energy storage was introduced into the system the power system was seen to be more stable compared to the system without energy storage. The percentage increase in the critical clearing time under the same load and fault condition was about 44.1%.The IEEE 9-Bus power system model with constant impedance load was used to determine how the critical clearing time (CCT), real and reactive power change during transients with and without the energy storage. The power flow equations were solved simultaneously to determine the system response. Simulation results showed how the energy storage affects the CCT and the real and reactive power supplied to the load during disturbances such as faults and changes in load.**

Keywords*— Power Systems , Distributed Generation, Power System Oscillations, Transient Stability, Reactive Power, IEEE 9-Bus System, Power System Analysis Toolbox, Critical Clearing Time

I. INTRODUCTION

The high depletion of conventional energy sources and increasing power demand has led the world into a wave of renewable and green energy revolution [1,2,3]. Remarkably, renewable energy offers a lot of opportunities since green energy sources maintain environmental protection by reducing the use of fossil fuel. However, introduction of the renewable energy into the power generation mix brings up the issues associated with distributed power generation. Notably, the instability associated with distributed generation resources because of the low inertia turbines must be taken seriously [4,5]. Accordingly, the power system stability has been recognized as an important issue for secure power system operation, especially in recent years that the power industries are moving towards deregulation and competition [6,7,8,9]. At the same time, modern electrical power systems are witnessing growing complexity due to increasing interconnections and installation of large generating units and extra-high voltage tie-lines etc. As such, short interruptions in electrical supply can have serious effect on the system.

Consequently, the stability of power systems has been and continues to be a major concern in power system operation. Power systems transient stability is mainly concerned about the behavior of the synchronous machine after disturbances [10,11,12,13]. Remarkably, the steady-state stability is a function of the operating conditions only, while the transient stability is a function of both the operating conditions and the disturbances and this makes the analysis of the transient stability to be more complex [14,15,16,17]. Transient signals are one of the causes of instability and they occur when there is a sudden change in the voltage or the current in a power system. Repeated analysis is required for different disturbances that are to be considered. In the transient stability studies, frequently considered disturbances are the short circuit faults of different types [18,19,20]. Out of these, the three-phase short circuit at the generator bus is the most severe type, as it causes maximum acceleration of the connected machine. Transient stability study, which is the main concern of this work, is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance, such as a fault on transmission facilities, sudden loss of generation, or loss of a large load [21,22,23,24,25]. It is an extension of the digital load flow calculation, which is made first to obtain the system conditions prior to the disturbance. The system response to such disturbances involves large excursions of generator rotor angles, power flow, bus voltages, and other system variables. As such, the main focus of this paper is to present a method for analyzing the transient stability of a multi-machine power system with energy storage. Particularly, the study will seek to determine the critical clearing time (CCT) of the system, obtain the performances of the system at different CCT with respect to different loads using MATLAB program and also determine the effect of energy storage on critical clearing time during fault.

II. METHODOLOGY

A. The Power System Model

The Institute of Electrical and Electronics Engineers (IEEE) nine bus system is a widely used test system template for variety of steady state and dynamic simulation studies by researchers and engineers to simulate new algorithms, especially pertaining to power system stability studies.Consider a three-machine nine-bus power system with one of the conventional synchronous generators (SG) replaced with a wind power distributed generator (DFIG) and load that is modeled as constant impedances as shown in Figure 1. Initial conditions and system data of the network are given in Tables 1 and 2. In a multi-machine generator system during a transient, each generator can oscillate, and the complexity of calculating the system trajectory during a transient increases with the number of generators.

The dynamic model used for the multi-machine system with energy storage is divided into three parts, namely; the synchronous generators model, the distributed generators model and the energy storage system model. The power system analytical model (PSAT) was used in this paper to model the system. The power system model without energy storage is shown in Figure 1.

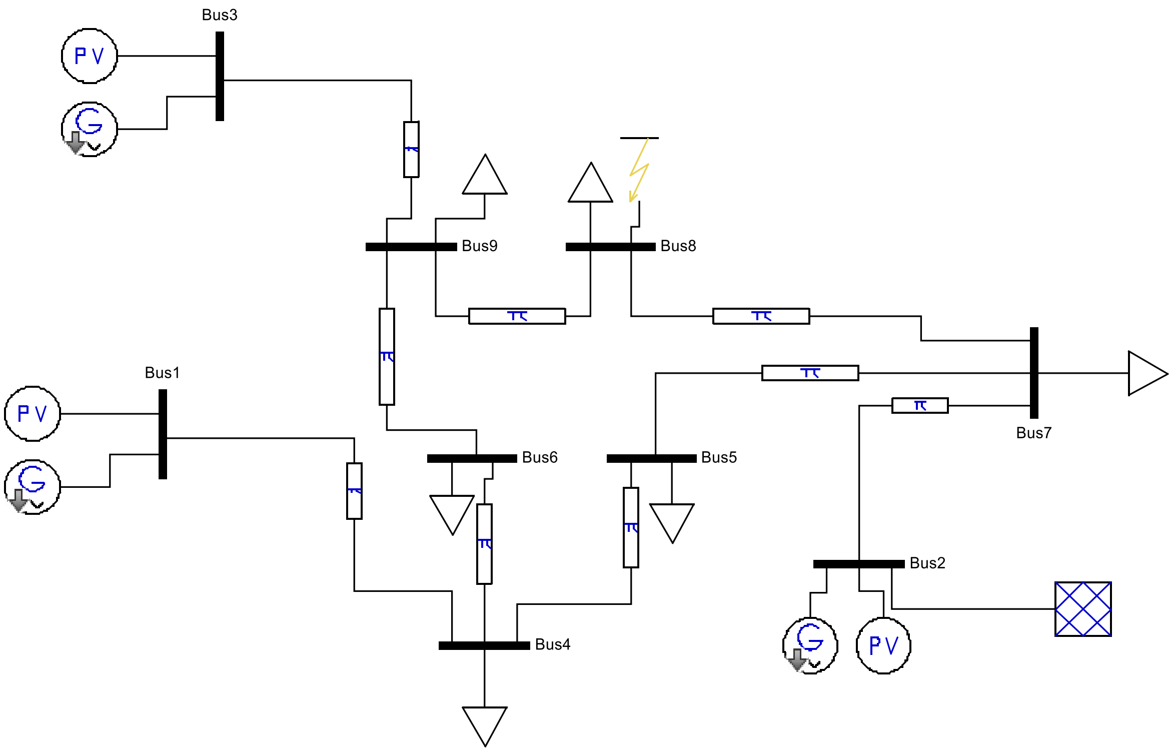

Figure 1: Power System model without energy storage

B. The Model For The Synchronous Generator And The Distributed Generator

In order to present the model for the synchronous generator and the distributed generator model , all the system data are first computed using a common unit of MVA, all the loads are also converted to equivalent constant impedances and the voltage causing the transient reactance is determined. The injected current (I_i) at the generator bus (that is the current before disturbance occurred) is given as;

$$I_i = \frac{S_i}{V_i} = \frac{P_i - jQ_1}{V_i}, i = 1, 2, 3 \dots \dots . n \quad (1)$$

Where n is the number of generators, V_i is the terminal voltage of the i^{th} generator, P_i and Q_i are the generator real and reactive powers respectively. The transient reactance is given as;

$$E^i = V_i + jX_d I_i \quad (2)$$

The loads are represented as constant admittance as follows;

$$y_{i0} = \frac{S^*}{|V_i|^2} = \frac{P_i - jQ_i}{|V_i|^2} \quad (3)$$

Then, the nodal equation of the system is given as;

$$I_{bus} = Y_{bus} V_{bus} \quad (4)$$

Where I_{bus} is the vector of the injected bus currents, V_{bus} is the vector of the bus voltages measured from the reference node. The Kron reduction formula is used to simplify the analysis by eliminating all nodes except the generator internal nodes, as follows;

$$\begin{bmatrix} 0 \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \\ Y^t{}_{nm} & Y_{mm} \end{bmatrix} \begin{bmatrix} V_n \\ E^i{}_m \end{bmatrix} \quad (5)$$

Where vector I_m denotes the generator currents and the generator and load voltages are represented by the vector E^i_m and V_n respectively, n is the number of buses to be removed.

The voltage vector V_n is eliminated by substitution which gives;

$$0 = Y_{nn} V_n + Y_{nm} E^1{}_m \quad (6)$$

$$I_m = Y^t{}_{nn} Y_{mm} + E^1{}_m \quad (7)$$

Hence;

$$I_m = Y_{bus}^{red} + E^1{}_m \quad (8)$$

$$I_m = Y^t{}_{nm} Y_{mm} E^1{}_m \quad (9)$$

The electrical power output of each machine is given as;

$$P_{ei} = \sum_{j=1}^{m} |E_i^1| |E_j^1| |Y_{ij}| cos(\theta_{ij} - \delta_i + \delta_j) \quad (10)$$

Before the disturbance occurred, the mechanical power is equal to the electrical power and it is given as;

$$P_{mi} = P_{ei} = \sum_{j=1}^{m} |E_i^1| |E_j^1| |Y_{ij}| cos(\theta_{ij} - \delta_i + \delta_j) \quad (11)$$

The multi machine system swing equation is given as;

$$\frac{H_i}{\pi f} \frac{d^2\delta}{dt^2} = P_{mi} - P_{ei} = P_a \quad (12)$$

$$\frac{H_i}{\pi f} \frac{d^2\delta}{dt^2} = P_{mi} - \sum_{j=1}^{m} |E_i^1| |E_j^1| |Y_{ij}| cos(\theta_{ij} - \delta_i + \delta_j) \quad (13)$$

Where Yij denotes the elements of the reduced bus admittance matrix during fault, H_i denotes the inertia constant of the machine i expressed on a common base. The following two state equations are solved in order to perform the transient stability analysis;

$$\frac{d\delta_i}{dt} = \Delta\omega i \quad (14)$$

$$\frac{d\omega_i}{dt} = \left(\frac{\pi f}{H_i}\right)(P_m - P_e) \quad (15)$$

The wind power model function is given as;

$$P_{wind} = \frac{1}{2} \rho A V_{wind}^3 \quad (16)$$

where: ρ is the air density, A is the area swept by blades , V_{wind} is the wind speed. The aerodynamic model is used to study the impact of wind fluctuation. The aerodynamic model consists of three subsystem; the aerodynamic efficiency, the tip-speed calculation and the torque calculation. The Tip-speed ratio is the ratio of blade-tip linear speed to wind speed and it is given as;

$$\lambda = K_b \left(\frac{w}{V_{wind}}\right) \quad (17)$$

C. Energy Storage System Model

The power system model with energy storage device is shown in Figure 2 the associated swing equation is given as;.

$$\frac{H_i}{\pi f} \frac{d^2\delta}{dt^2} = P_{mi} - P_{ei} = P_a \quad (18)$$

Where: H is the inertia constant, P_m is the mechanical power, P_e is the electrical power.

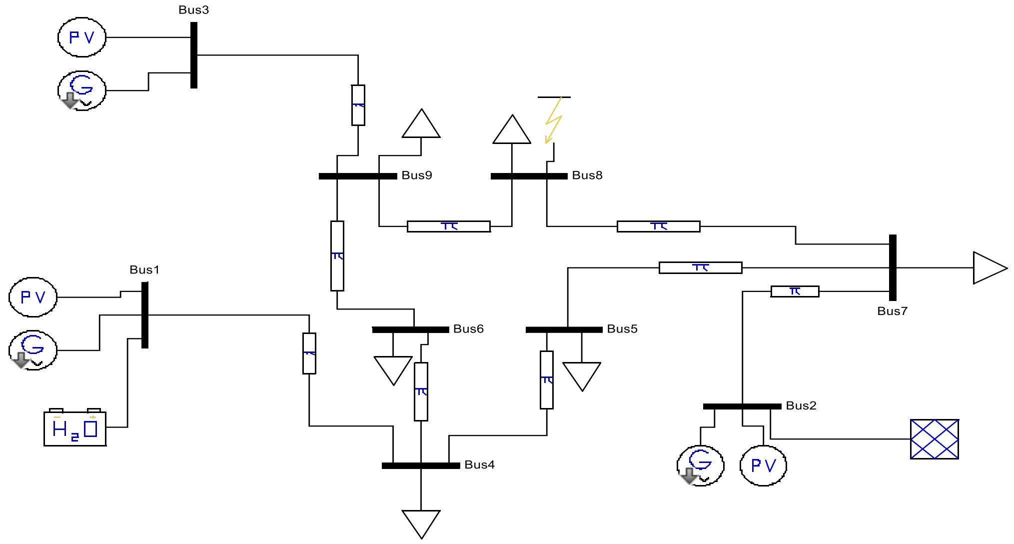

Figure 2: Power System Model with Energy Storage Device

In Figure 2, the energy storage device was placed on bus 1, which is the bus most affected by disturbance due to its nature (i.e. DFIG). Buses 1,2 and 3 are the generation with synchronous machines and buses 4, 5,6,7,8 and 9 are the load buses. Neglecting stator winding resistance, the electrical power delivered by a rotational machine is given as;

$$P_e = \frac{|E_a||V_t|}{X_s sin\,\delta} \quad (19)$$

Where: $E_a$is the machine internal voltage. V_t is the terminal voltage, X_s is the synchronous reactance. Eventually, after considering other relevant factors, the swing equation of a machine with energy storage device is given as;

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e \pm P_s = P_a \pm P_s \quad (20)$$

Where: $P_s$is the power supplied or absorbed by the storage device.

If Equation 16 is linearized with $\Delta P_m = 0$, it becomes;

$$\frac{H}{\pi f}\frac{d^2\Delta\delta}{dt^2} = -K\Delta\delta \quad (21)$$

Where: K is the synchronizing power coefficient.

$$K = \frac{dP_e}{d\delta} = \frac{|E_a||V_t|}{X_s} cos\delta_0 \quad (22)$$

From Equation (16) and Equation (19), to keep the machine running in a balanced condition, Pa has to be close to zero. The machine will maintain its stability if this power is provided or absorbed by an energy storage device during the disturbance. Therefore, the energy storage device should provide power equal to the right hand side of Equation (19) given as;.

$$P_s = \frac{|E_a||V_t|}{X_s} cos\delta_0 \Delta\delta \quad (23)$$

In order to ensure that the machine does not enter the unstable region, the power angle deviation is allowed to be 0.60° which is 1% of the angle margin. Therefore,

$$P_s = \frac{|E_a||V_t|}{X_s} cos\delta_0 \Delta\delta = \frac{|E_a||V_t|}{X_s} cos(30^o) \times 0.60 \left(\frac{\pi}{180}\right) \Delta\delta \quad (24)$$

$$P_s = 0.00907 \frac{|E_a||V_t|}{X_s} \quad (25)$$

Since $|E_a|$ and $|V_t|$ are close to 1.0 p.u., the required energy storage size can be approximated to:

$$P_s \approx \frac{0.00907}{X_s} \quad (26)$$

The flowchart of the design with energy storage is given in Figure 3 while Table 1 shows the load data and the line data including the transformer data.

Table 1 : The load data and the line data including transformer data

Load Data			Line Data including Transformer Data			
Bus No	Load (MW)	Load (Mvar)	From Bus	To Bus	R (p.u.)	X (p.u.)
1	0	0	1	4	0.0000	0.0576
2	0	0	2	7	0.0000	0.0625
3	0	0	3	9	0.0000	0.0589
4	0	0	4	5	0.0100	0.0850
5	125.0	50.0	4	6	0.0170	0.0920
6	90.0	30.0	7	5	0.0320	0.1610
7	0	0	7	8	0.0085	0.0720
8	100.0	35.0	8	9	0.0119	0.1008
9	0	0	9	6	0.0390	0.1700

Table 2: Generator data

Bus No	Generator Type	Voltage Mag.	Generation (MW)	Mvar Limits	
				Min	Max
1 2 3	Synchronous Generator Synchronous Generator Distributed Generator	1.06 1.04 1.00	71.2 163 85.5	0 0 0	27.1 6.7 95.19

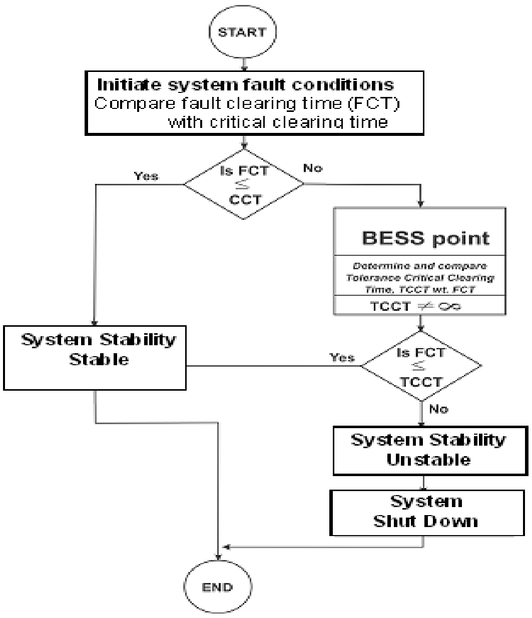

Figure 3: Flowchart of the design with energy storage

III. SIMULATION, RESULTS AND DISCUSSION

The wind power plant used in this paper is modeled as an aggregate of around 57 GE 1.5MW DFIG wind generators. The wind power plant has a total capacity of 95.19 MVA, which is the same as the synchronous generator 3 in IEEE 9 bus system. The transient stability of the system is based on the application of three-phase fault. At bus k in the network , a solid three-phase fault result in Vk = 0. In order to reflect the alteration in the network, the bus admittance matrix is recalculated each time the fault is cleared and this may be achieved by the removal of the faulty line. Afterward the post-fault reduced bus admittance matrix is evaluated and the post fault electrical power of the ith generator is also determined from Equation (10).

The simulation is repeatedly conducted with the post-fault power to determine the system stability, until the plots reveal a definite trend that clearly shows the stability or instability of the power system. Generally the slack generator is designated as the reference machine and is plotted. The system is considered to be stable if the angle differences fails to increase, however, the system is considered unstable if any of the angle differences increases indefinitely.

A. The Simulink Model

A program was written in Matlab programming language. This program is used to analyze the transient stability of a multi-machine network subjected to a balance three-phase fault. The program prompts the user to enter the faulted bus number and the line numbers of the removed faulty line. In this work a three-phase fault occurred at bus eight (8) as depicted in Figure 4 .

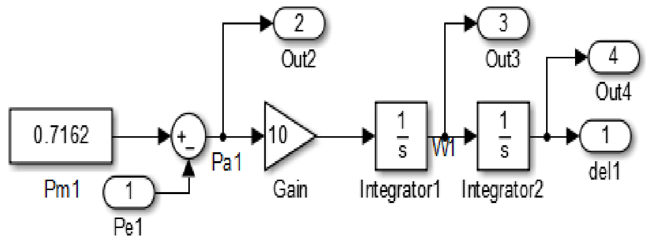

Figure 4. : Simulation diagram for accelerating power and angular velocity of eachgeneratorrotor

When the fault is cleared, which may involve the removal of the faulty line (as done in this work) the bus admittance was recomputed to reflect the change in the network. Next the post fault angle is evaluated and the post fault electrical power for each of the three generators are simulated from Equation (10). Using the post-fault power, the simulation is continued to determine the system stability, until the plots reveals a definite trend as regards the stability or instability of the system. If the the angle differences do not increase, the system is stable. If any of the angle diffrences increases indefinitely, the system is unstable. The generator 1 is selected as the reference machine. In order to reduce fluctuation of electrical power of the wind plant (i.e. generator 3) storage device supplying a constant amount of power (suitable for transient stability studies) during deceleration.The complete three generator systems is illustrated in Figure 1. Figure 5 is the entire simulation diagram of the system for transient stability analysis. Figure 6 shows the Simulation diagram that compute power of the energy storage device, P_S, as function of time

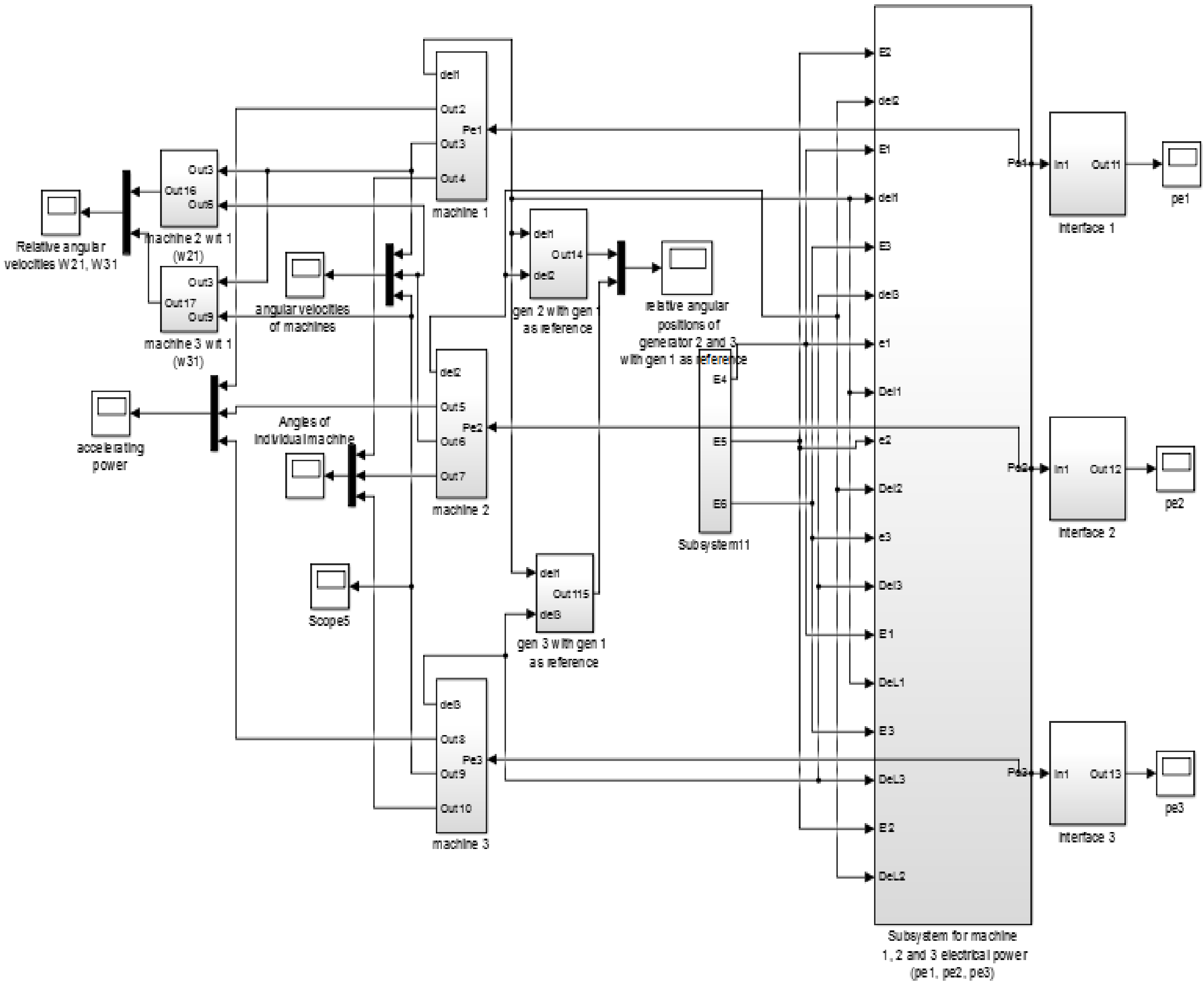

Figure 5: 9-Bus System used for transient stability analysis

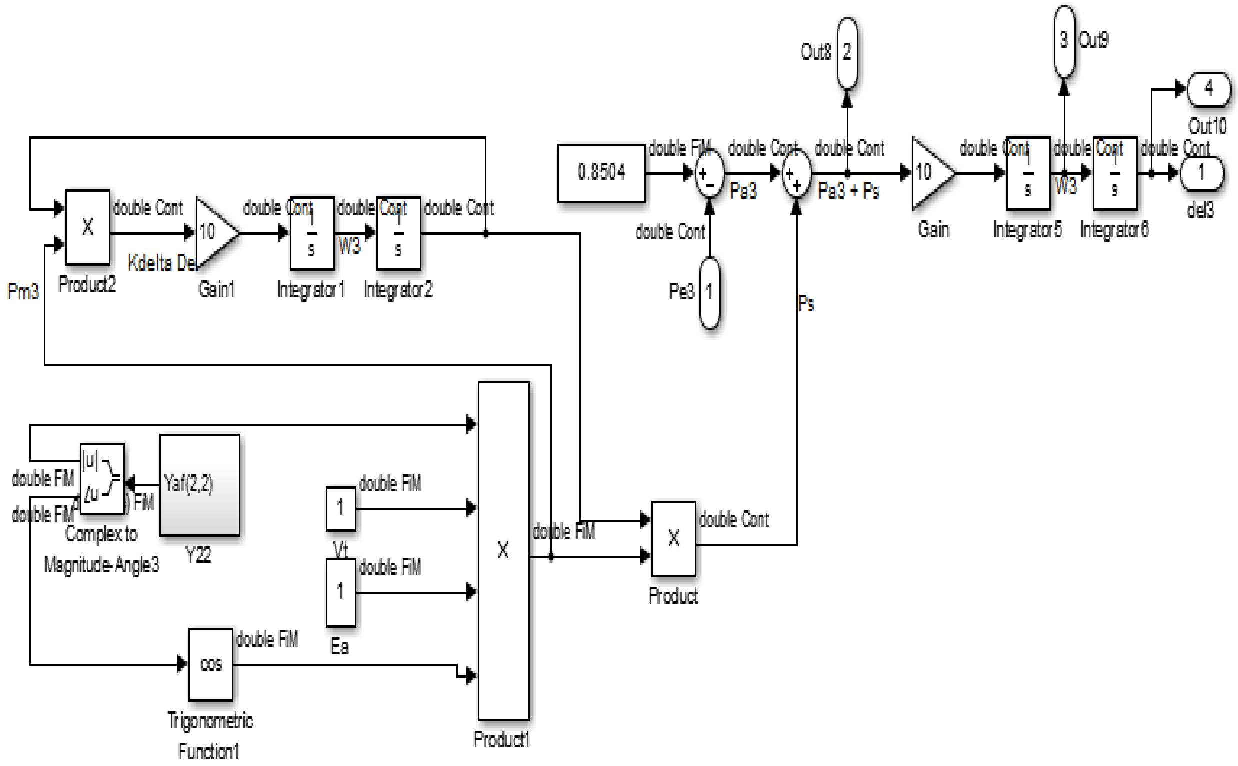

Figure 6: A simulation diagram that compute power of the energy storage device, P_s, as function of time

Admittances matrix for each network condition, that is, pre-fault, fault and post fault is givven as;

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{bmatrix} \begin{bmatrix} V_n \\ V_r \end{bmatrix} \quad (27)$$

Where n is the generator node and r is the remaining node, theerfore we have;

$$\mathrm{I}_n = Y_{nn}V_n + Y_{nr}V_r \quad (28$$

After solving, the reduced matrix is given as;

$$Y_R = \frac{I_n}{V_n} = (Y_{nn} - Y_{nr}{Y_{rr}}^{-1}Y_{rn}) \quad (29)$$

The reduced Y matrix for each condition are (for Pre-fault condition);

$$Y_{R\,p.f} = \begin{bmatrix} 0.8455 - 2.9883j & 0.2871 + 1.5129j & 0.2096 + 1.2256j \\ 0.2871 + 1.5129j & 0.4200 - 2.723j & 0.2133 + 1.0579j \\ 0.2096 + 1.2256j & 0.2133 + 1.0879j & 0.2770 - 2.368j \end{bmatrix} \quad (30)$$

The reduced Y matrix during fault condition is given as;

$$Y_{R\,d.f} = \begin{bmatrix} 0.6568 - 3.8160j & 0 & 0.0701 + 0.6306j \\ 0 & 0 - 5.4855 & 0 \\ 0.0701 + 0.6306j & 0 & 0.1740 - 2.7957j \end{bmatrix} \quad (31)$$

The reduced Y matrix after fault condition is given as;

$$Y_{R\,a.f} = \begin{bmatrix} 1.386 - 2.2960j & 0.1290 + 0.7603j & 0.1824 + 1.0637j \\ 0.1290 + 0.7063 & 0.3745 - 2.0150j & 0.1921 + 1.2067j \\ 0.1824 + 1.0637 & 0.1921 + 1.2067j & 0.2691 - 2.3516j \end{bmatrix} \quad (32)$$

The reduced Y matrix before disturbance condition is given as;

$$P_{mi} = P_{ei} = {E_i}^2 G_{ii} + \sum_{j=1}^{n} E_i E_j\, Y_{ij} \cos\theta_{ij} - \delta_i + \delta_j \quad (33)$$

Where the Y_{ij} is the transfer admittance between nodes i *and* j and Y_{ii} is the driving point admittances of nodes i.

$$P_a = P_{mi} - P_{ei} \quad (34)$$

Where $P_{m1} = 0.7162$; $P_{m2} = 1.6298; P_{m3} = 0.8504; Gain = 10; E_1 = 1.0566$; $E_2 = 1.0802$; $E_3 = 0.0170$; and $Out\ 1 = Out\ 2$

B. Simulation Result

Simulations were carried out in MATLAB using the data in Table 1 and Table 2 to examine the behavior of the system. Fault was introduced on line 8 of the model without energy storage and the fault clearing time was obtained. Plots of angular positions of the generators, angular velocity of the generators and accelerating power of the generators were obtained with and without energy storage device.

C. At Fault Clearing Time (FCT) Of 3 Seconds Without Energy Storage

The results of the simulation shown in Figure 7, Figure 8 and Figure 9 with fault clearing time of 3 seconds without energy storage show the angular positions of each machine; the relative angular plot of the machine as well as the relative velocities of the generators after the fault is cleared. Figure 7 shows the plot of the angular position of bus 1 without energy storage, Figure 8 shows the plot of angular position of bus 2 without energy storage and Figure 9 shows the plot of angular position of bus 3 without energy storage. From Figure 7, Figure 8 and Figure 9 shows that on clearing the fault on the machine after 3 seconds, the machines are seen to be running together although the accelerating power of generator 3 is very low.

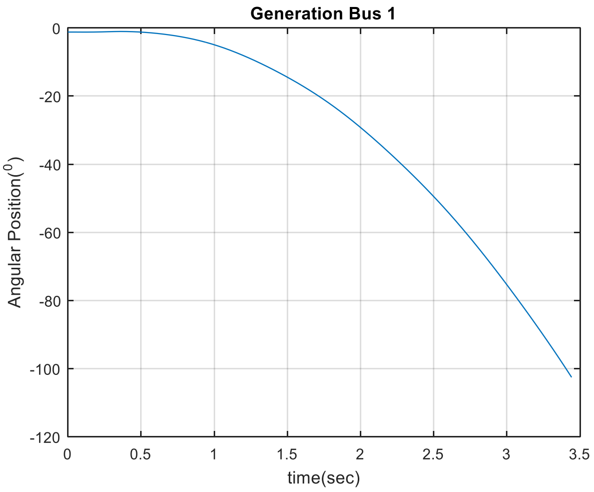

Figure 7: Plot of angular position of bus 1 without energy storage

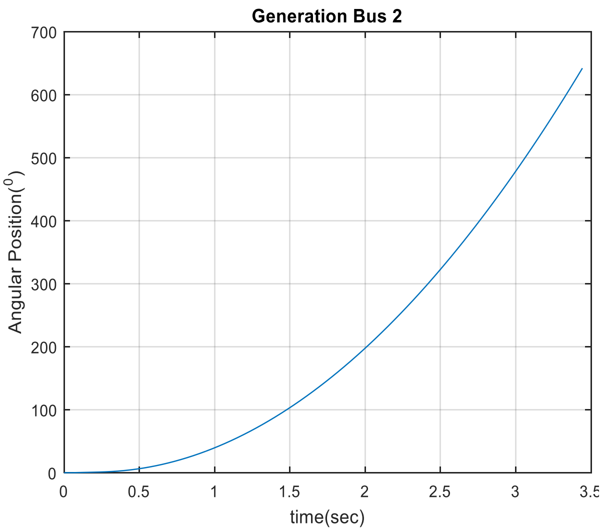

Figure 8: Plot of angular position of bus 2 without energy storage

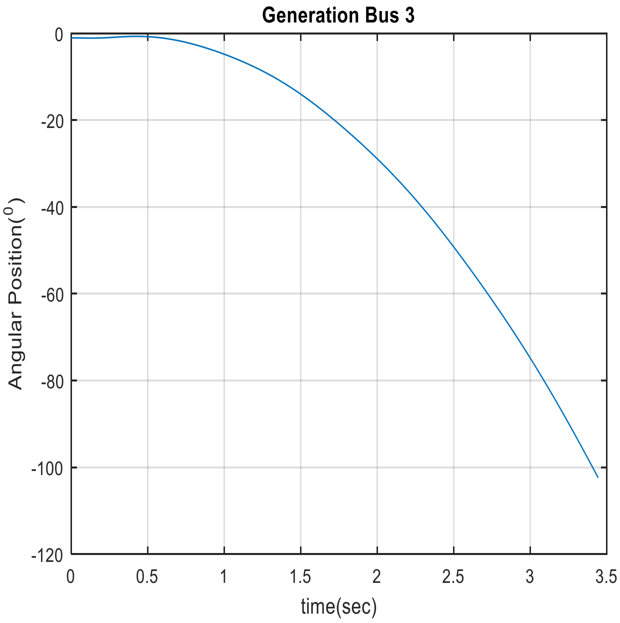

Figure 9: Plot of angular position of bus 3 without energy storage

Figure 10 shows the plot of angular position of individual generators, Figure 11 shows the plot of relative angular positions, Figure 12 shows the plot of relative angular velocities and Figure 13 shows the plot of generator accelerating powers.

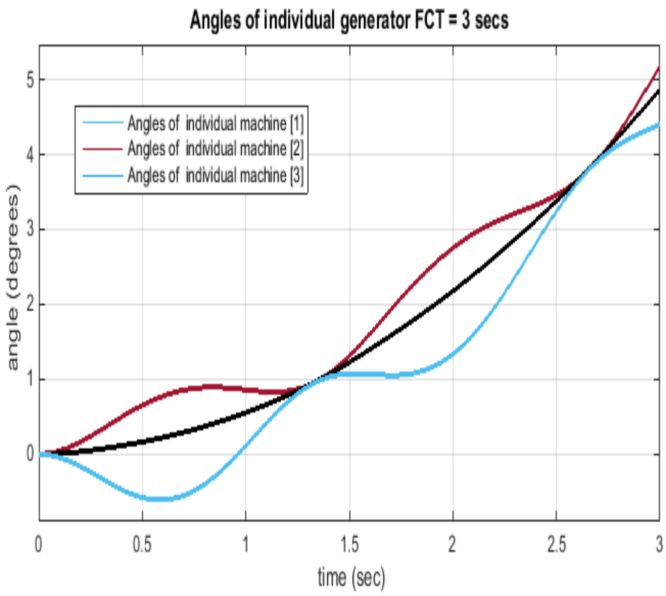

Figure 10: Plot of angular position of individual generators

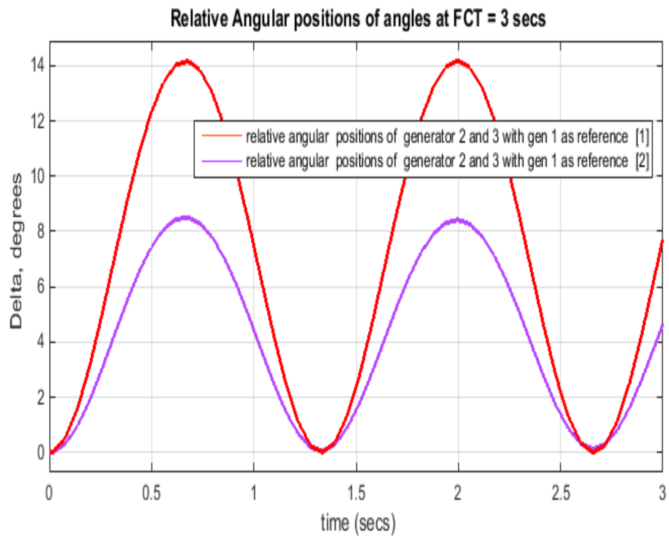

Figure 11: Plot of relative angular position

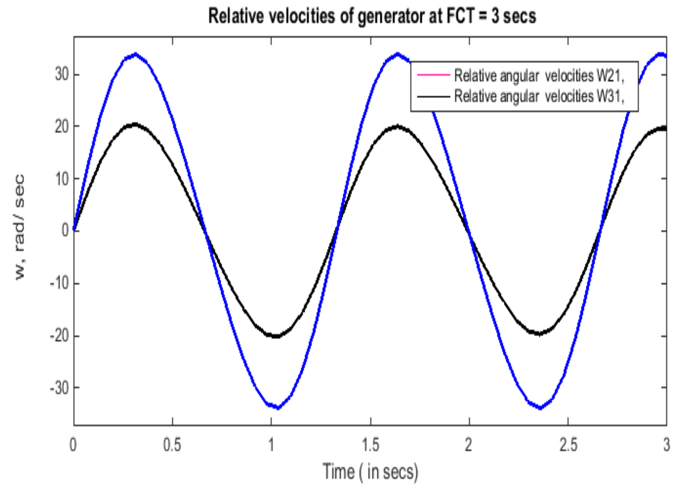

Figure 12: Plot of relative angular velocities

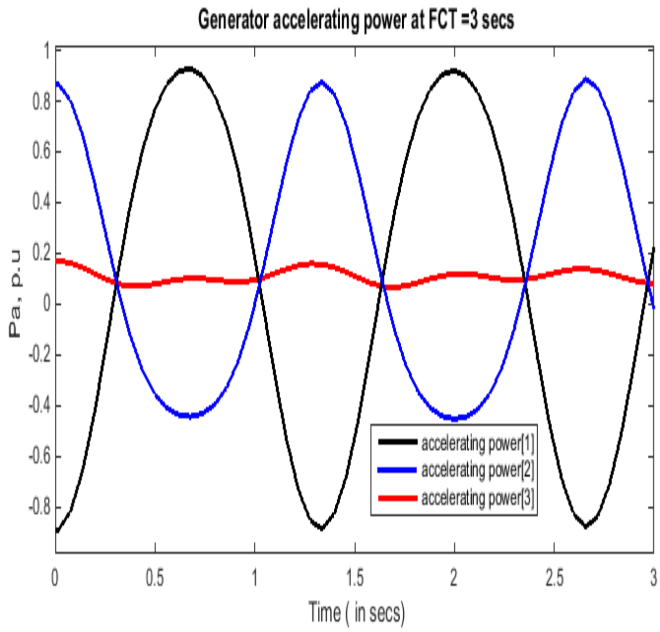

Figure 13: Plot of generator accelerating powers

D. At Fault Clearing Time (FCT) Of 3.4426 Seconds Without Energy Storage

The fault clearing time was increased to 4 seconds under the same fault conditions. The plots of the relative angular position of the generators, the relative angular velocities of the generator as well as the accelerating powers of the generators after the fault was cleared are shown in Figure 14, Figure 15 and Figure 16 respectively. When the fault was cleared, the shape of the plot of relative angular velocity versus time and accelerating power versus time were observed to be broken noticeably at the turning points of the curve. Hence, the system was unstable.

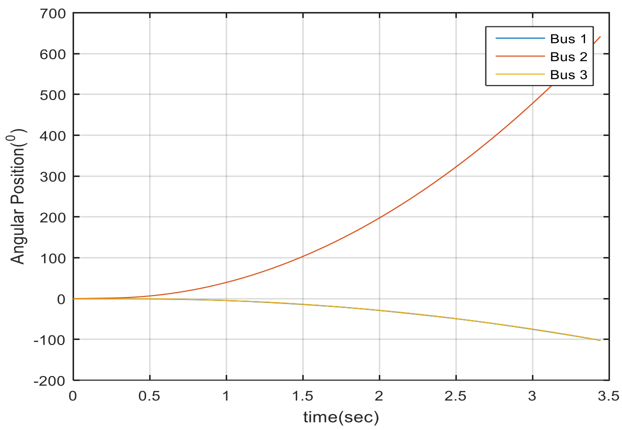

Figure 14: Plot of angular position without energy storage

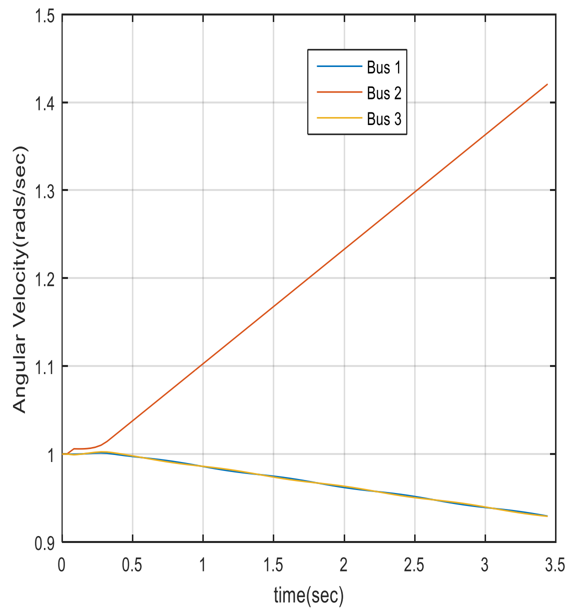

Figure 15: Plot of angular velocity without energy storage

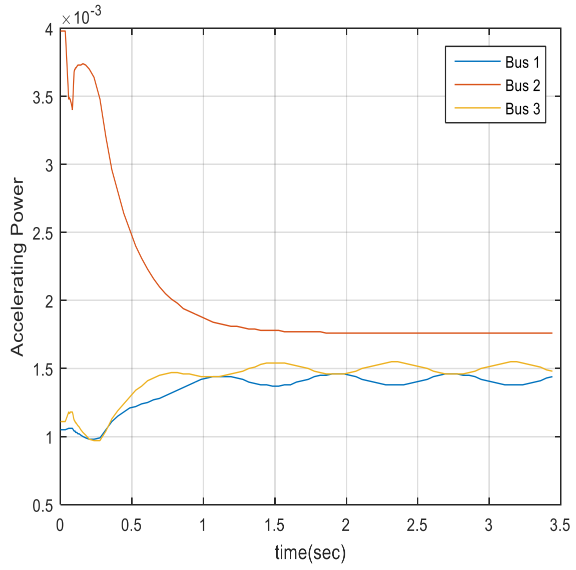

Figure 16: Plot of accelerating power without energy storage

E. At FCT Of 4 Seconds With Energy Storage

Battery energy storage system was connected to the distributed generator G3 and the simulation was repeated for fault clearing time of 3 seconds and 4 seconds under the same fault conditions. The battery energy storage system is such that can absorb energy during fault. The system was stable at 3 seconds and at 4 seconds when the fault was cleared plots of angular positions plot of each machine, the relative angular position of the machine, the relative velocities of the generators and the machine accelerating power after the fault was cleared were taken as shown in Figure 17, Figure 18 and Figure 19.

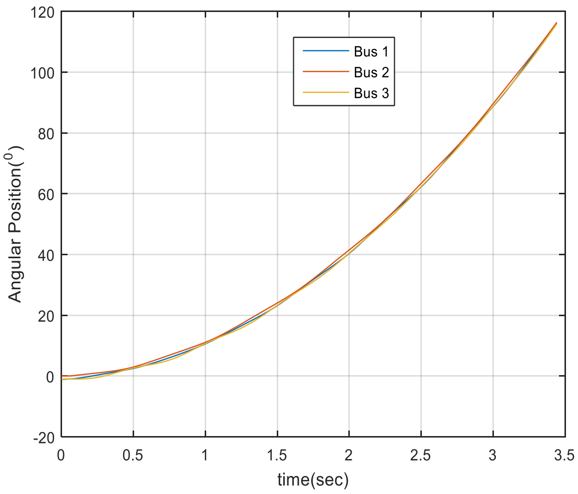

Figure 17: Plot of angular position with energy storage

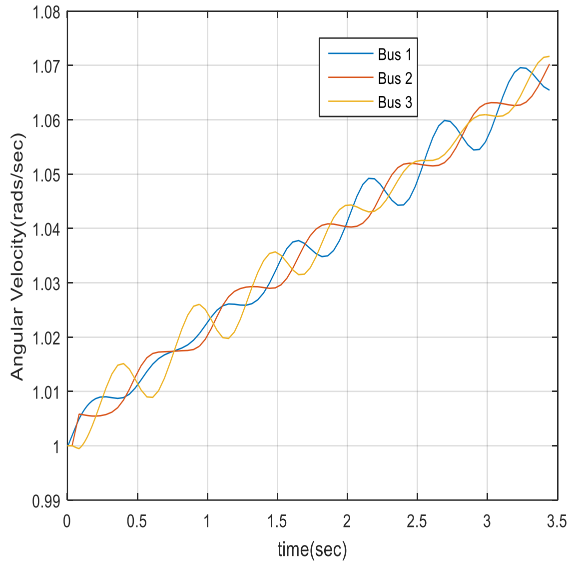

Figure 18: Plot of angular velocity with energy storage

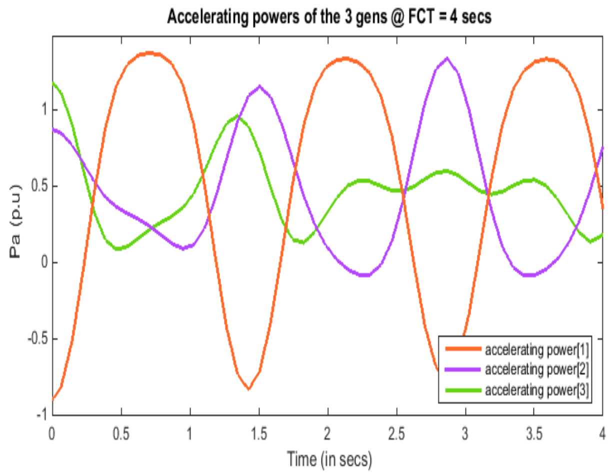

Figure 19: Plot of accelerating power with energy storage

IV CONCLUSIONS

A complete model for transient stability study of a multi-machine power system was developed using Matlab/Simulink. It is basically a transfer function and block diagram representation of the system equations. Power System Analytical (PSA) tool in Mathlab was used to model the system at different fault clearing time (FCT) because it contains state of the art tools for a detailed study and parameter optimization. Basically, for a transient stability study the model facilitates fast and precise solution of the nonlinear differential equations through the use of the swing equation. The user can easily select or modify the solver type, step sizes, tolerance, simulation period output options etc. with the help of an appropriate menu from within the Simulink software.

Particularly, the MATLAB/SIMULINK model of a three machine 9-Bus power system was used to study the role of energy storage systems in improving transient stability. In the study, it was assumed that the energy storage system can absorb constant power during a fault. The focus was on determining the critical clearing time (CCT) of the system, obtaining the performances of the system at different CCT with respect to different loads in MATLAB and to investigate the effect of energy storage on critical clearing time during fault. Through the analysis it was determined whether the system is stable or unstable for a particular fault clearing time when subjected to a three-phase fault.

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