Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Development of Gas Turbines Model in MATLAB to Investigate Response in the Event of Major System Contingencies

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Abstract -- **Most power plants consists of gas turbines generators to produce electrical power. These types of plants are preferred by power providers as it can provide high efficiency. This is the case too in Malaysia, in which most power plants consists of gas turbine generators. In recent years, Malaysia had experienced several large-scale blackout incidents. It was found that some of these incidents would have survived without a blackout if the inadvertent generator tripping did not occur. Therefore, investigation into the response of gas turbine generators during major transmission system contingencies must be conducted. In order to do so, the gas turbine generator would have to be accurately modeled. This can be performed easily in the PSS/E software using the present gas turbine models available. This paper provides an optional method for modeling gas turbine (GT) generator systems using MATLAB / Simulink.**

I. INTRODUCTION

A combined cycle power plant, which combines a gas turbine and a steam turbine, can achieve high energy efficiency. The turbines are combined in one cycle, so that the energy in the form of heat flow or a gas flow is transferred from one of the turbines types to another. The plant mainly consists of a gas turbine, a waste heat recovery boiler, and a steam turbine [1]. This type of plant has high energy efficiency which exceeds 50%. As in many countries, many combined cycle plants have been installed in Malaysia.

However, in recent years, Malaysia had experiences several large-scale blackout incidents [2]. In the latest incident occurring in 2005, following a frequency drop of about 1.5 Hz, several gas turbine plants sequentially tripped out inadvertently. The total generation loss was 5760 MW. Because of its importance, several studies were made to observe responses of combined cycle power plants to frequency drops [3] – [5]. These models were based on gas turbine models developed by Rowen [6] and Mello et. al [7] to represent practical plants, and then used to calculate responses to frequency changes. However, detailed analysis on how plant variables behave for frequency drops has not been made. This requires the ability to observe the output from each transfer function block within the gas turbine generator model which cannot be achieved using PSS/E software environment in which only selected output variables and states can be observed.

This paper presents a method for modeling GT systems (consisting of the generator, exciter and governor) using MATLAB / Simulink to observe its response during a major system contingency. Simulink is a well known graphical interactive tool for modeling, simulation and analysis. Simulink provides set of standard and custom libraries to allow accurate models of control systems to be created. Because Simulink is integrated with MATLAB, the underlying facility of MATLAB is available to Simulink. Simulink is used across a broad range of industries for the design, simulation and analysis of control systems, therefore it would be a benefit to utilize the power of Simulink to perform the modeling and simulation of AC generator excitation and governor systems of synchronous generators in a real network [8]. In addition, the MATLAB / Simulink environment was chosen because it enables users to easily observe the output from each block within the model built.

The GT generator systems to be modeled consist of a governor, gas turbine, excitation system and synchronous generator as shown in Figure 1.

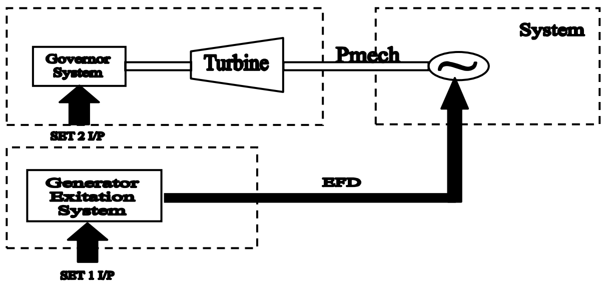

Fig. 1. Block diagram of generator excitation and governor systems for a generator connected to a network.

II. MODELING OF GAS TURBINE IN MATLAB

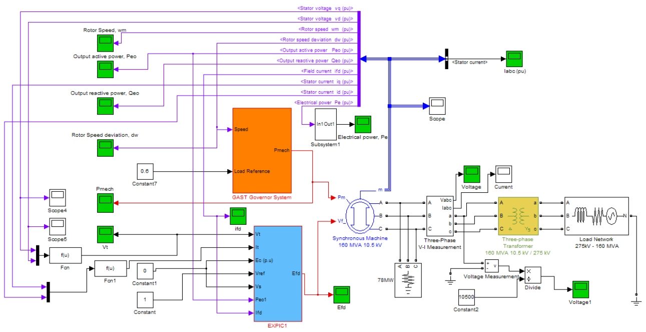

Fig. 2. Plant A GT generator system model in Simulink

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The GT model available in PSS/E was rebuilt in MATLAB / Simulink based on the model block diagrams available in PSS/E manual. A GT generator system for a particular open-cycle power plant in Malaysia, here onwards called plant A, was chosen to be modeled in MATLAB which consists of the governor (based on the GAST model in PSS/E), excitation system (based on the EXPIC1 model in PSS/E), and synchronous generator (based on GENROE model in PSS/E). In order to observe the behavior of the GT model during a frequency disturbance, the modeled GT system must be connected to a Thevenin-equivalent load network via a step-up transformer.

A. Model GAST

GAST represents the principal dynamic characteristics of industrial gas turbines driving generators connected to electric power systems. Speed variations from nominal are expected to be small (approximately 5%). The model consists of a forward path with governor time constant, T_1, and a combustion chamber time constant, T_2, together with a load-limiting feedback path. The load limit is sensitive to turbine exhaust temperature, and T_3 represents the time constant of the exhaust gas measuring system. The constant, K_T, is used to adjust the gain of the load-limited feedback path.

The load-limited feedback path only controls fuel flow to the gas turbine through the low valve gate, when its output is lower than the original load reference (decremented by the droop signal, 1/R). The damping coefficient, D_{turb}, is used to represent speed damping introduced by the gas turbine rotor.

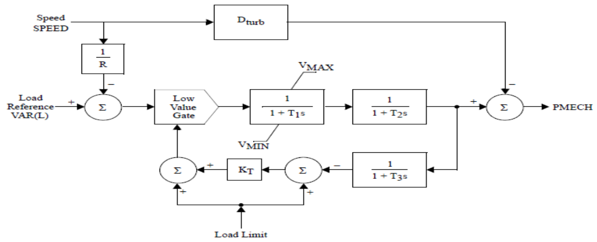

Fig. 3. Model of GAST in PSS/E

TABLE I provides a description of the parameters employed in the GAST model available in PSS/E.

TABLE I
DESCRIPTION PARAMETERS OF GAST

Notation	Definition
IBUS	Bus number where model is located
'GAST'	Gas Turbine Governor Model
I	Machine number
R	Governor permanent droop
T_1	Governor time constant
T_2	Combustion chamber time constant
T_3	Exhaust gas measuring system time constant
A_T	Ambient temperature load limit
K_T	Constant to adjust the load-limited feedback
V_{MAX}	Maximum fuel valve opening
V_{MIN}	Minimum fuel valve opening
D_{turb}	Speed damping introduced by gas turbine rotor

The GAST model was successfully built in MATLAB Simulink as shown in Fig. 4. The 'MinMax' block in Fig. 4 performs the same function as 'Low Value Gate' in Fig. 3, which is to choose either the temperature control or acceleration control operation. In Fig. 4, the limit V_{MAX} and V_{MIN} of the fuel valve opening is set by the 'Saturation' block.

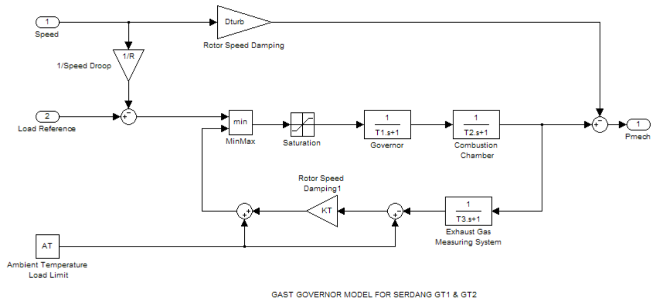

Fig. 4. Governor Model GAST in Simulink

B. Model GENROE

The inputs to the generator model are mechanical power P_m, field voltage from the exciter E_{fd} and terminal bus voltage V_T. The outputs of the generator are as shown in Fig. 5.

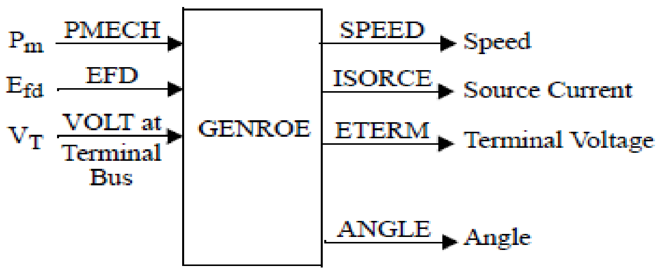

Fig. 5. Round Rotor Generator Model (Exponential Saturation) in PSS/E

TABLE II
DESCRIPTION PARAMETERS OF GENROE

Notation	Definition
IBUS	Location at bus
GENROE'	Generator model type
I	Machine number
T'_{do}	Transient Open-Circuit time constant (d-axis).
T''_{do}	Subtransient Open-Circuit Time Constant (d-axis).
T'_{qo}	Transient Open-Circuit time constant (q-axis).
T''_{qo}	Subtransient Open-Circuit Time Constant (q-axis).
H	Inertia
D	Speed Damping
X_d	Synchronous Reactance (d-axis).
X_q	Synchronous Reactance (q-axis).
X'_d	Transient Reactance (d-axis).
X'_q	Transient Reactance (q-axis).
X''_d	Subtransient Reactance (d-axis).
X_l	Stator Leakage Inductance
$S_{(1.0)}$	Saturation factor
$S_{(1.2)}$	Saturation factor

In MATLAB Simulink SimPower System blockset, there exists a standard block to dynamically model a synchronous generator. Hence, this standard generator model was employed in modeling of the Plant A gas turbine, the parameters of the generator are shown in Fig. 6.

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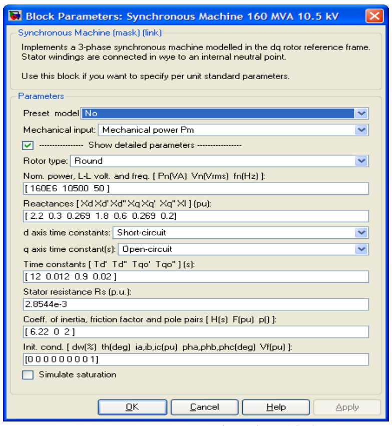


Fig. 6. Synchronous Generator Parameters in Simulink

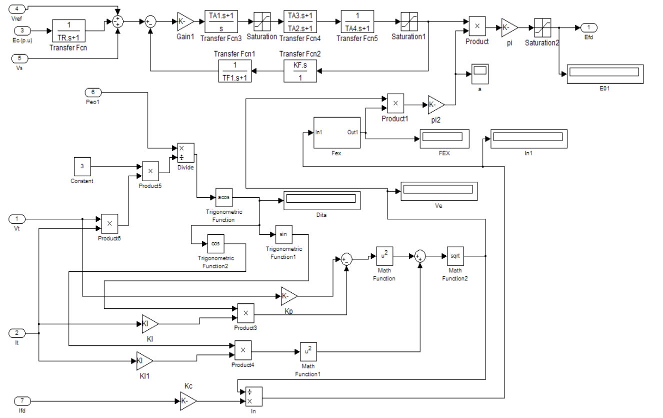


Fig. 8. Excitation Model EXPIC1 in Simulink

C. Model EXPIC1

EXPIC1 is recommended to be used for excitation systems whose voltage regulator control element is a proportional plus integral type (PI).

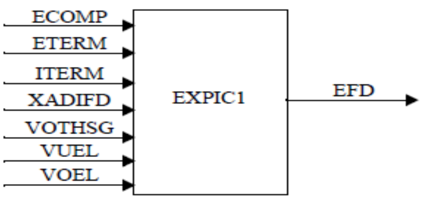
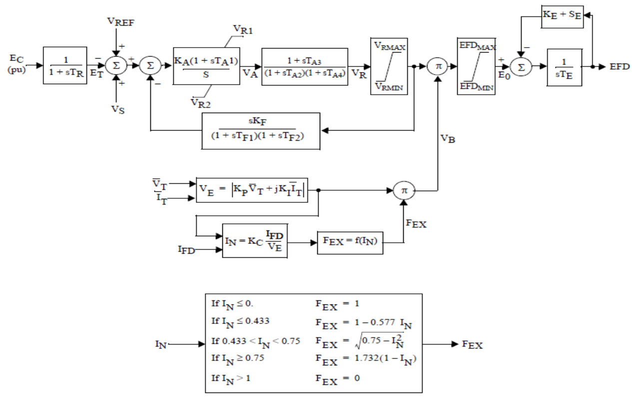


Fig. 7. Proportional/Integral Excitation System



If ($K_P = 0$ and $K_I = 0$), then $V_B = 1$.
If $T_E = 0$, then EFD = E_0.
V_S = VOTHSG + VUEL + VOEL

Fig. 9. EXPIC1 in PSS/E

The EXPIC1 model was successfully built in Simulink as shown in Fig. 8. During the testing of EXPIC1, it was observed that an error was obtained if the value of T_e was set to zero (as is the case for the Plant A GT exciter). From the PSS/E manual, and as shown in Fig. 9, it was noted that when T_e is zero, EFD = E_0. Hence, the blocks containing K_e and S_e (as shown in Fig. 9) were removed in the Simulink model of EXPIC1 and E_0 was directly connected to the output E_{fd}. The most difficult part was to build the magnitude of V_E which was obtained from the phasors $\overline{V}_T$ and $\overline{I}_T$ using the following equations:

$$\begin{aligned} V_E &= \left| K_P \overline{V}_T + jK_I \overline{I}_T \right| \\ &= \left| K_P V_T \angle 0 + jK_I I_T \angle \theta \right| \\ &= \left| K_P \left(V_T \cos 0 + jV_T \sin 0 \right) + jK_I I_T (\cos\theta + j\sin\theta) \right| \\ &= \left| \left(K_P V_T + jK_I I_T \cos\theta - K_I I_T \sin\theta \right) \right| \\ &= \sqrt{\left(K_P V_T - K_I I_T \sin\theta \right)^2 + \left(K_I I_T \cos\theta \right)^2} \end{aligned} \quad (3.1)$$

where $\theta = \cos^{-1}\left(\dfrac{P_{eo}}{3V_T I_T} \right)$, (3.2)

P_{eo} = Output electrical power of generator

III. RESULTS

The completed GT generator system model would have to be verified in order to determine the accuracy of the model reconstruction in MATLAB / Simulink. Therefore, the model was simulated in MATLAB / Simulink under steady-state conditions and under a frequency injection test.

A. Steady-state Conditions

In order to ensure correct modeling of the individual block in the GT system, the behaviour of the system under steady-state conditions would have to be obtained. Fig. 10 to Fig. 19 show the output obtained from the steady-state simulation of Plant A at 60% load. It can be observed that the GT system is able to supply the required power to the load within twenty seconds. The results obtained are as expected.

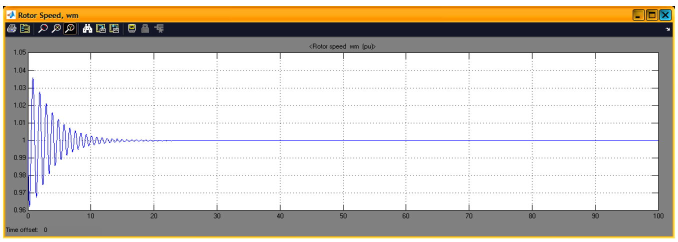


Fig. 10. Rotor speed, ω_m

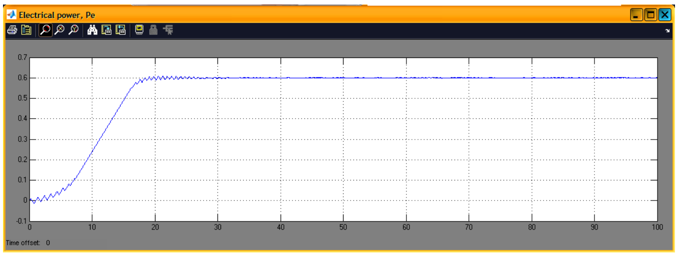


Fig. 11. Electrical power, P_e

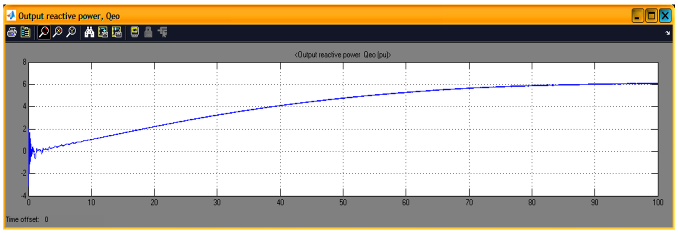


Fig. 12. Output reactive power, Q_{eo}

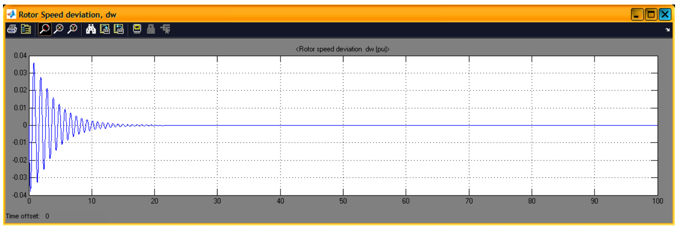


Fig. 13. Rotor speed deviation, dω

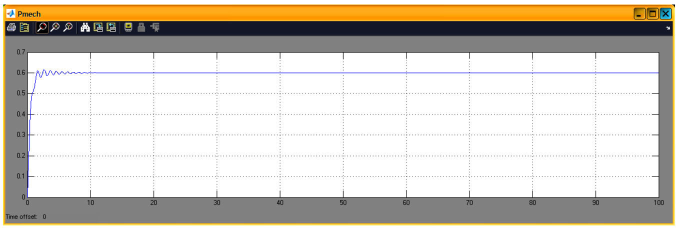


Fig.14. Mechanical power, P_{mech}

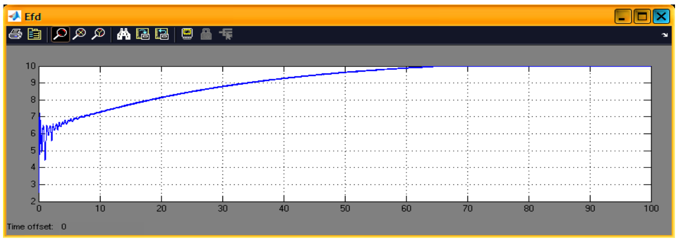


Fig. 15. Field voltage, E_{fd}

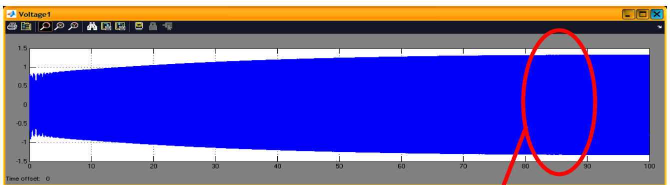


Fig. 16. Per-unit output phase voltage, V_{out}

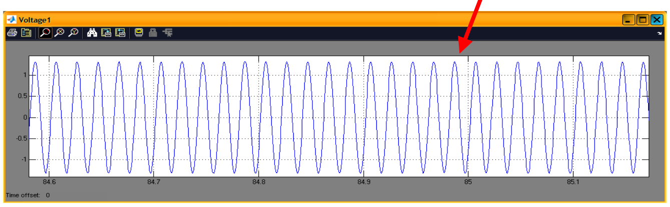


Fig. 17. Zoom in area of output voltage from Fig. 16. (50 Hz of sinewave)

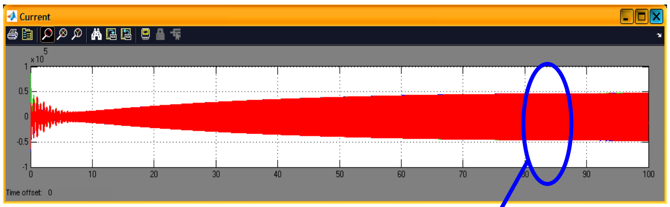


Fig. 18. Output current, I_{out}

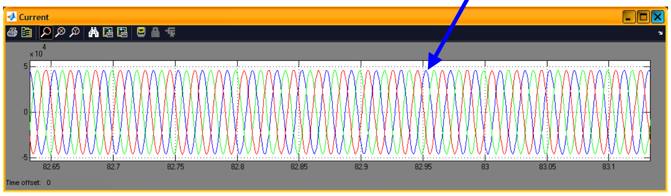


Fig. 19. Zoom in Area of Output Current from Fig. 18. (50 Hz of sinewave)

The results obtained from the simulation were then verified with results obtained from the exact model built in PSS/E under the same test conditions.

B. *Frequency Injection Test*

To investigate the behaviour of the gas turbine system during a major transmission system disturbance, the GT model of Plant A developed in Simulink were subjected to two types of frequency injections which are ramp response and step response. For each of the response (ramp and step), + 0.5 Hz injection was applied shown in Fig. 20 and Fig. 25. The frequency injection is subjected onto the GT after it has achieved steady-state which is approximately 80 seconds after the GT is started.

All the above frequency injection tests were simulated onto each GT system under four different in-house loads (between synchronous generator and three-phase transformer) conditions, i.e. 60%, 70%, 80% and 90% of rated load. In all the Simulink models, the injection is applied to the rotor speed deviation, dω signal.

As the load is increased, the + 0.5 Hz ramp frequency injection causes a reduction in the electrical power P_e by a value of 0.01 p.u. as shown in Fig. 21 to Fig. 24. However, the system was able to restore the P_e to the original amount within 3 seconds for all the load conditions.

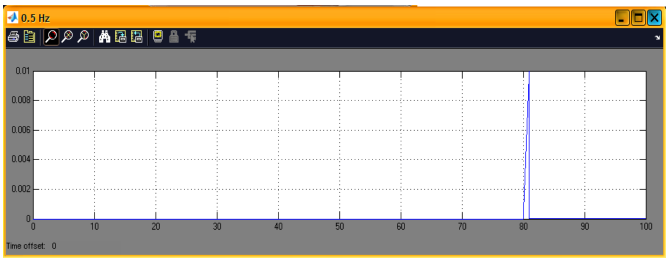


Fig. 20. Ramp Test of 0.5 Hz with 60%, 70%, 80% and 90% of load for Plant A

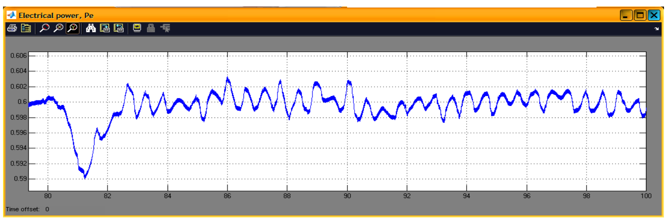


Fig. 21. Electrical Power, Pe (0.5 Hz Ramp Test with 60% load for Plant A)

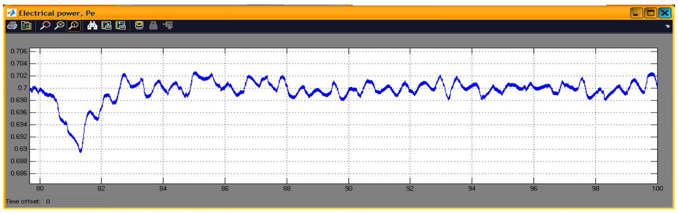


Fig. 22. Electrical Power, Pe (0.5 Hz Ramp Test with 70% load for Plant A)

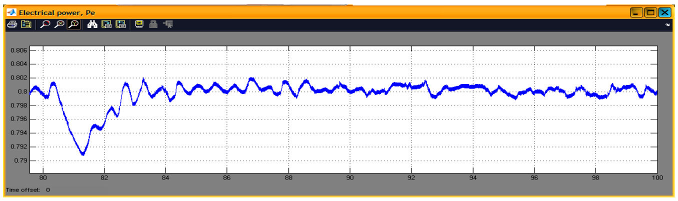


Fig. 23. Electrical Power, Pe (0.5 Hz Ramp Test with 80% load for Plant A)

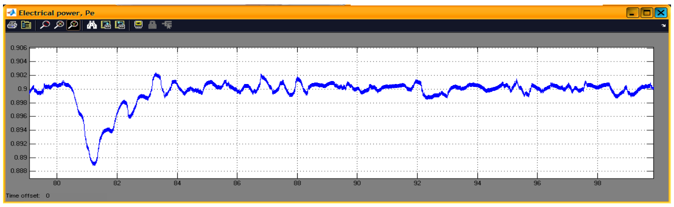


Fig. 24. Electrical Power, Pe (0.5 Hz Ramp Test with 90% load for Plant A)

Fig. 25 shows the electrical power produced by Plant A modeled in PSS/E when subjected to a +0.5 Hz ramp frequency injection test under 60%, 70%, 80% and 90% rated load conditions. Comparing the results for electrical power obtained in Simulink (Fig. 21 to 24) with that from PSS/E (Fig. 25), the amount of drop in electrical power under all load conditions are the same which is approximately 2 MW or 0.015 p.u as seen in Fig. 25. The only difference is that the GT system simulated in Simulink recovered at a much faster rate (approximately 10 times faster) than the system simulated in PSS/E. This could be due to the fact that a load flow analysis was not performed on the Simulink GT system prior to the frequency injection test simulation causing the Simulink GT system and PSS/E system to have different initial system conditions. Note that in PSS/E, a load flow analysis on the GT system is automatically performed whenever the frequency injection test is simulated. The noise observed in the Simulink output (Fig. 21 to 24) is introduced by the numerical solver employed by Simulink during the simulation.

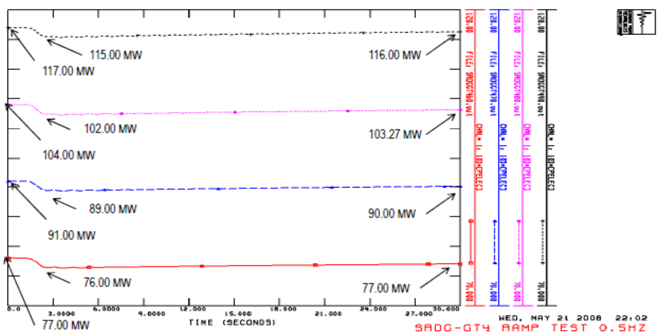


Fig. 25. Electrical Power from PSS/E in 0.5 Hz Ramp Test

As the load is increased, the + 0.5 Hz step frequency injection causes a reduction in the electrical power P_e by a value of 0.02 p.u. as shown in Fig. 27 to Fig. 30 for the Simulink GT model. However, the system was able to restore the P_e to the original amount within 2 seconds for all the load conditions.

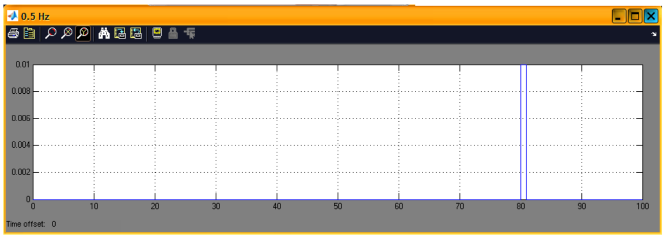


Fig. 26. Step Test of 0.5 Hz with 60%, 70%, 80% and 90% of load for Plant A

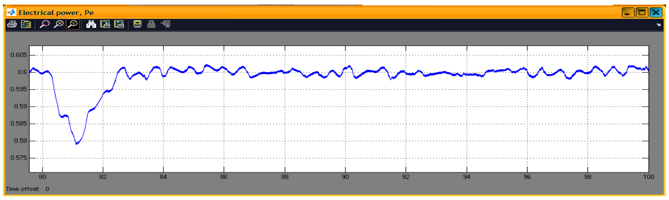


Fig. 27 Electrical Power, Pe (0.5 Hz Step Test with 60% load for Plant A)

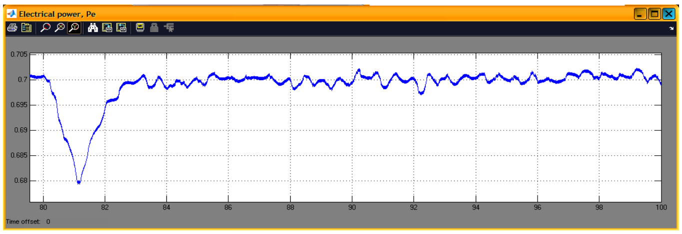


Fig. 28 Electrical Power, Pe (0.5 Hz Step Test with 70% load for Plant A)

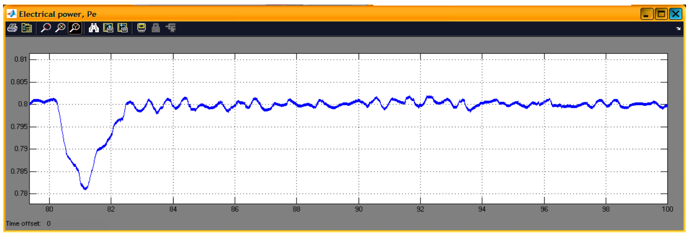


Fig. 29 Electrical Power, Pe (0.5 Hz Step Test with 80% load for Plant A)

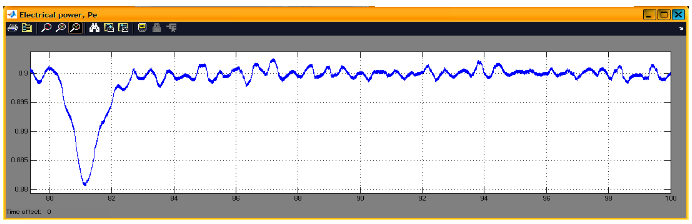


Fig. 30 Electrical Power, Pe (0.5 Hz Step Test with 90% load for Plant A)

Fig. 31 shows the electrical power produced by Plant A modelled in PSS/E when subjected to a +0.5 Hz step frequency injection test under 60%, 70%, 80% and 90% rated load conditions. Comparing the results for electrical power obtained in Simulink (Fig. 27 to 30) with that from PSS/E (Fig. 31), the amount of drop in electrical power under all load conditions are the same which is approximately 1.2 MW or 0.01 p.u. as seen in Fig. 31. The only difference is the shape of response whereby the electrical power obtained from Simulink had a damped response compared to the oscillatory response obtained in PSS/E. This could be due to the fact that a load flow analysis was not performed on the Simulink GT system prior to the frequency injection test simulation causing the Simulink GT system and PSS/E system to have different initial system conditions. Note that in PSS/E, a load flow analysis on the GT system is automatically performed whenever the frequency injection test is simulated. The noise observed in the Simulink output (Fig. 27 to 30) is introduced by the numerical solver employed by Simulink during the simulation.

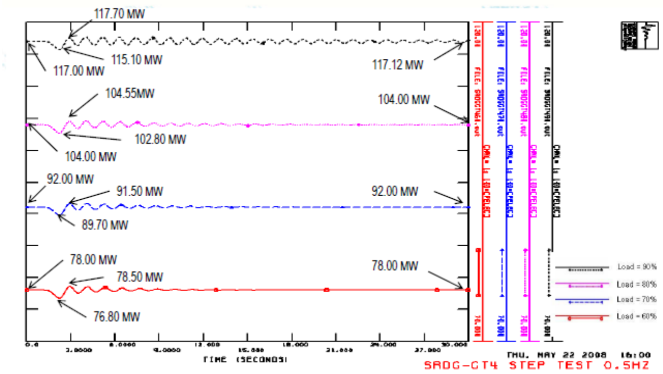


Fig. 31 Electrical Power from PSS/E in 0.5 Hz Step Test

IV. CONCLUSION

This paper has introduced and implemented a method of modeling GT by using MATLAB / Simulink. The simulation results obtained from the model were found to be comparable with the results from PSS/E. From the ramp and step frequency injection test results, it was observed that Plant A Simulink-modeled systems produced comparable electrical power magnitude results with PSS/E. Only slight differences in electrical power response shape and rise/fall time were observed. This proves that the GT system models developed in Simulink are verified and can be used to observe GT response during a major system disturbance.

The advantage of having the MATLAB / Simulink GT model is the ability to visually observe the output from each block within the GT system in order to ascertain the system behavior during major system contingencies which is not possible in PSS/E

V. REFERENCES

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