

Investigation of Parameters on Small Signal Stability of 206.1 MVA Generators

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Abstract: This research was investigation on small signal stability on two generators. The analyses were based on the single machine infinite bus with the increasing load as 25% of 175 MW and 85 MVAR. It was yielded the damping ratios, oscillating frequencies and stability conditions. Furthermore, it could be calculated the system synchronizing and damping constants. The results for the active and reactive powers and for the terminal and bus voltages in both generators were the same as the oscillating in 8-9.3 sec. The chosen data for the computations were at the time before the increasing load in 7.8 sec with every sampling oscillation as 0.05 sec. The results were the system in asymptote stables with the 0.0043-0.0044 damping ratios, 1.2108-1.2132 Hz for oscillating frequencies, around 1.47 pu torque for synchronizing constant and 0.50 pu torque per changing speed for the damping constant.

Key words: Asymptote stable, damping constant, damping ratio, synchronizing constant, small signal stability, oscillation

INTRODUCTION

Stability is a ability of system to remain stable in face of interference. The stability plays an important role in an electric grid system. Therefore, the generation should be remained in a stable condition, both in the face of small and large disturbances. The small disturbances in a generator can disturb the frequency, load and voltage on the system. They are caused by minor changes at the load and generation such as accretion rotor angle due to lack of synchronization and insufficient torque of rotor oscillation damping. The ability of system to be stabilized in the synchronous system due to minor disturbances is called small-signal stability (Kundur, 1994). Stability is the most important constraint in power system operation (Saini *et al.*, 2013; Sabapathi, 2015; Sulistiawati *et al.*, 2012; Gan *et al.*, 2000). A damping of oscillations has been recognized as important in power system operations. Oscillations among generators appeared as soon as the generators operate in parallel and it tend to be continually excited (Grigsby, 2012). The synchronous generator may sometimes be able to withstand a large impact but it may fail to retain synchronism under a small impact due to growing oscillations (Bunnoon, 2013; Maity *et al.*, 2013). The general concepts were associated with applying power system stabilizers utilizing shaft speed, AC bus frequency and electrical power inputs (Ranjan *et al.*, 1993; Vu and Turitsyn, 2016; Amin and Aqilah, 2013; Patel *et al.*, 2002; Salim and Ramos, 2012;

Larsen and Swann, 1981; Pavella *et al.*, 2000). The eigenvalue will influence the limits on power system that contains oscillations due to variety of interactions among components. The small signal stability analysis is very useful due to interaction of distributed energy resources with the utility system. It was possible to improve the small-signal stability margin by including constraints on the eigenvalue real parts. The use of energy storage enhanced the small-signal stability (Lerm *et al.*, 2001; Dong, 1998; Kumar *et al.*, 2009; Ogata, 2002; Gulvender, 2016; Condren and Gedra, 2006; Canizares *et al.*, 2017; Kanchanaharuthai, 2012). The system dynamic behavior can be described by following vector-matrix form (Kundur, 1994):

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{f}) \quad (1)$$

Where:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \dots \\ x_n \end{bmatrix}, \mathbf{u} = \begin{bmatrix} u_1 \\ \dots \\ u_n \end{bmatrix}, \mathbf{f} = \begin{bmatrix} f_1 \\ \dots \\ f_n \end{bmatrix}$$

The column vector \mathbf{x} leads the state vector and its inputs x_i is a state variable. While, the column vector \mathbf{u} declares the input system, t is expressed in its own time and derivative of state variable \mathbf{x} with respect to time.

There were many researches those related to stability and voltage collapse, especially, in the Self-Excited Induction Generators (SEIGs) and Doubly Fed Induction Generators (DFIGs) (Rajambal *et al.*, 2009; Sun *et al.*, 2013;

Shawon *et al.*, 2013; Adachi and Yokoyama, 2016; Shi *et al.*, 2011; Vittal *et al.*, 2009; Mishra *et al.*, 2009; Pozhahana *et al.*, 2016). Nevertheless, this research was focused on the synchronous generators, another type of induction generators.

The research related to small signal stability of generators is need to be further developed. Usually, the analysis on the stability involves only one or some behaviors of parameters and less consider to the real parameters on a generator. Therefore, it was necessary to investigate the more parameters on the small signal stability simultaneously and considering the real generator parameters. The parameters were not dawdled. The objectives of research were to obtain the small signals, based on the 206.1 MVA generator parameters in the form of relationship on the additional incoming load, the output signals of active and reactive powers, the terminal and system bus voltages of generators. Furthermore, it was determined the stability of system during small disturbances, parameters of small signal stability such as synchronous constant, damping constant, damping ratio and the oscillating frequency during small disturbance. Besides that, it was identified the problems of small signal stability values of oscillating frequency in the generation system. The analyzing signal changes of active power, reactive power, voltage terminals and bus voltages during small disturbances using the simulations. The analysis was performed in the machine infinite bus and the two typical generators.

MATERIALS AND METHODS

Figure 1 describes the research stages in the analysis of generator small-signal stability shortly. First step, it should be done was to collect the data of generation system.

Furthermore, the system was modeled in a block diagram, that the generator supplied power to the system infinite bus. The next step was simulating the model, where the single line is shown in Fig. 2a.

The data were analyzed by using the simulations, which could then be computed the parameters to form a state matrix. Furthermore, it was obtained the eigenvalues of system and it was known from the real values whether the system was stable or not. If the value was the real negative, the system asymptote was stable, otherwise the system was unstable. It could also, be obtained the value of damping ratio, oscillating frequency, synchronous constant and the damping constant. The model block diagram of small-signal stability can be seen in Fig. 2b. While, the modeling for the excitation system is shown in Fig. 3 (Anonymous, 2015).

In a small-signal stability analysis, it should be noted that the study was conducted when the condition of interruption was in the flow and flux linkage, so that, it

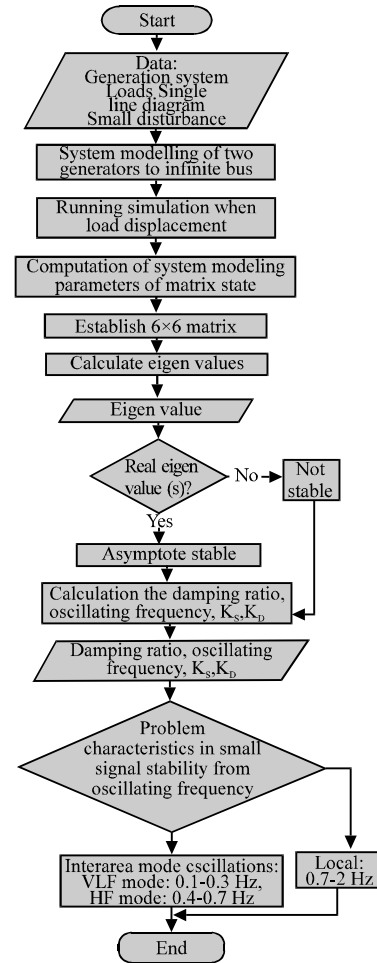


Fig. 1: Flow chart research stages

was need to add an incremental saturation factor. The matrix was mainly influenced by the field changes, revealed as:

$$p \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\psi_{fd} \\ \Delta v_1 \\ \Delta v_2 \\ \Delta v_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32(incr)} & a_{33(incr)} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\ a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\psi_{fd} \\ \Delta v_1 \\ \Delta v_2 \\ \Delta v_3 \end{bmatrix} + \begin{bmatrix} b_{11} \\ 0 \\ 0 \\ 0 \\ b_{51} \\ b_{61} \end{bmatrix} \Delta T_m \quad (2)$$

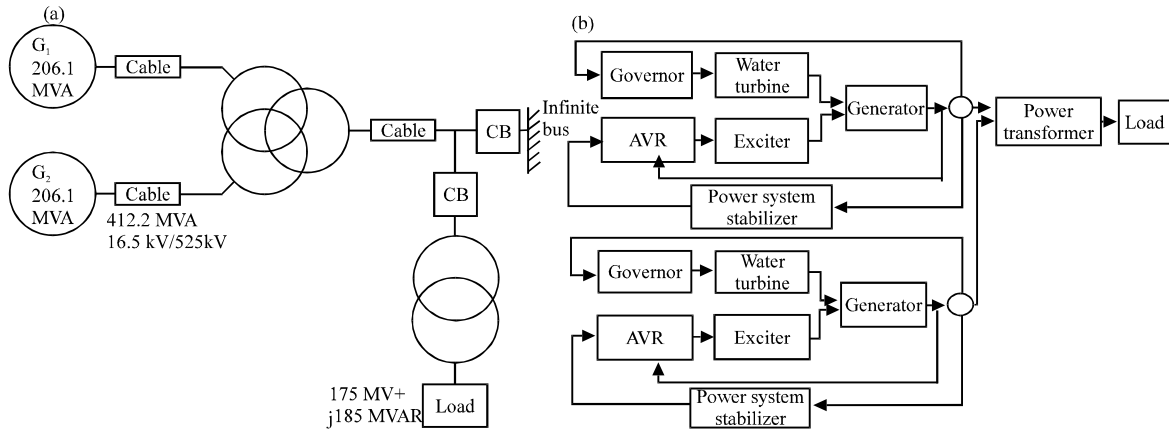


Fig. 2: a) System model of two generators and b) Small signal stability block diagram

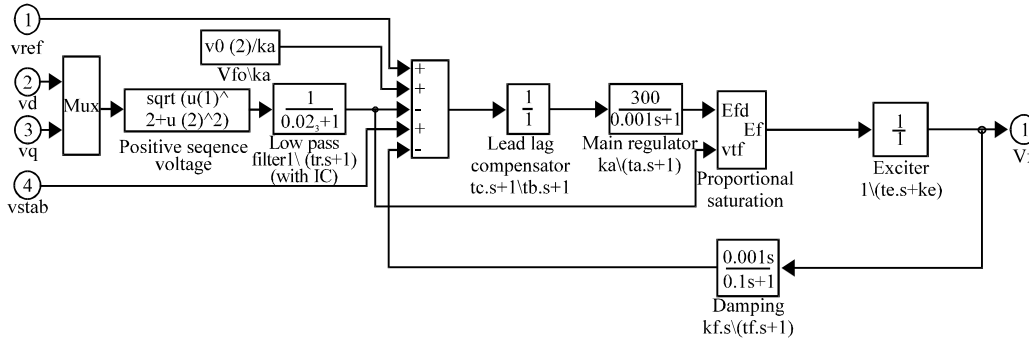


Fig. 3: Block diagram of excitation system

From the eigenvalues of state-matrix, it would be calculated the values of damping ratio and oscillating frequency, so that, the problems could be identified whether as local or global problems. The local problems could be distinguished by two causes, namely when the generator suffered from a rotor angle oscillation, commonly called a local plant mode oscillation and at a fraction generator adjacent experiencing oscillation or called as intermachine or interplant mode oscillation. Both oscillations might be identified by the oscillation frequencies between 0.7 and 2 Hz. Otherwise, the global problem was caused by an interaction among generators largely as an interarea mode oscillation. Based on the oscillation frequencies, it could be divided into two categories as very low and higher frequencies. The former involved all generators in the system with the frequency range between 0.1 and 0.3 Hz and the latter ranged between 0.4 and 0.7 Hz.

RESULTS AND DISCUSSION

In this study, it was used two identical generators where the parameters can be listed in Table 1.

Table 1: Generator parameters

Parameters	Values
S (MVA)	206.1
V (kV)	16.5
I (kA)	7.212
f (Hz)	50
pf	0.85 lagging
n	333 (rpm)
Reactance (pu) 1 pu = 1.32 Ω	
X_{ds}	0.93
X_{du}	1.09
D_d'	0.199
X_d''	0.128
X_q	0.65
X_d''	0.151
X_2	0.142
X_1	0.134
X_o	0.105
Time constant (sec)	
T_{do}'	12.8
T_d'	2.22
T_d''	0.063
T_a	0.20

The small-signal stability calculations were required AVR, exciter and PSS. These parameters were also, identical for two generators as shown in Table 2.

Figure 4 shows that the generator experienced an oscillation when starting in the beginning of the system

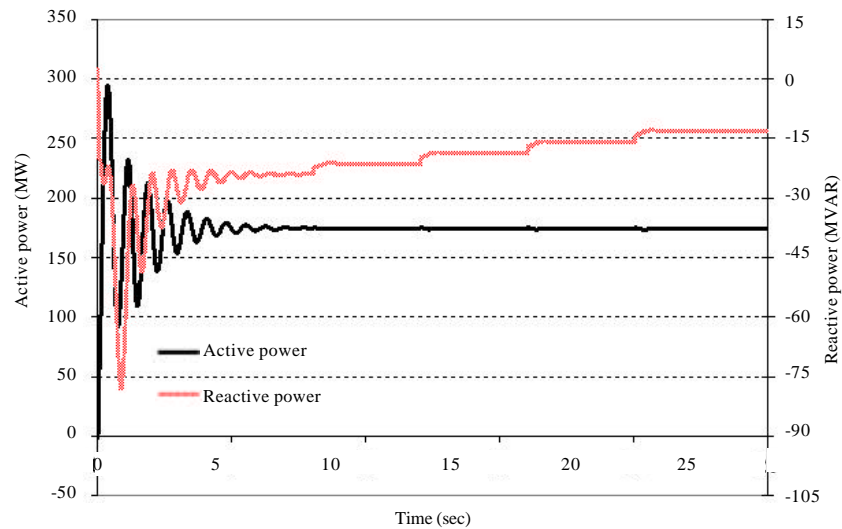


Fig. 4: Active and reactive power charts of generator 1

Table 2: Excitation system and PSS parameters

Parameters	Values
Excitation system	
$T_f(\text{sec})$	20×10^{-3}
K_a	300
$T_d(\text{sec})$	0.001
K_e	1
T_e	0
$T_b(\text{sec})$	0
$T_c(\text{sec})$	0
K_f	0.001
$T_f(\text{sec})$	0.1
$E_{fmin}(\text{pu})$	-11.5
$E_{fmax}(\text{pu})$	11.5
K_p	0
$V_{to}(\text{pu})$	1
$V_{to}(\text{pu})$	1.00712
PSS	
Sensor time constant	30×10^{-3}
Gain	0.5
Wash-out time constant	2
T_1	50×10^{-3}
T_2	0.2
V_{min}	-0.2
V_{max}	0.2

in the second 0-7 and that time, there was an additional load on the second of 8, 12, 16 and 20. The active and reactive power oscillations at the baseline or starting were occurred due to plant or system seeking an equilibrium point when connected to the infinite bus. Nevertheless, this oscillation was still within the safe ability limits of system itself. The highest magnitude was occurred on the second of 0.35 as 294.6 MW and at the second of 0.55, decreased as 199.4 MW. This meant that the highest oscillation was occurred for 0.2 sec. For every new equilibrium condition, the system would experience a dense oscillation for 0.08 sec for early adaptation.

Otherwise, the reactive power also, experienced an oscillation, however, it had a different behaviour. It tent to increase, especially, on the additional loads at 8, 12, 16 and 20 sec.

The figure described the active power oscillations of the generator 1, due to the additional load of 175 MW and 85 MVAR with the oscillations that more dense from 8-8.06 sec where the rest of oscillations tent to swing down to the steady state in 9.3 sec. This occurrence was caused the system search for a new equilibrium point. The system to warded to the steady state after 1.3 sec oscillation. The active power oscillation itself reached the maximum point of 154.57 MW when in 8.05 sec. In this simulation, the generator 1 and 2 were typical, so, the active power which issued for both generators were the same, when starting and oscillation.

In a contrast to active power that occurred during the dense oscillation of 0.06 sec, the reactive power oscillation signal that was densely occurred during 0.08 sec whether when searching for a new equilibrium state with the largest magnitude of -25.63 MVAR when oscillation in second of 8.05 or -19.168 MVAR when starting. The reactive power of generator 1 was in a leading state because the generator was shortage of reactive power, so that, it utilized amount of reactive power on the infinite bus. Besides that, this case was to keep the voltage in amount corresponding to the infinite bus itself. As load addition, the reactive power also experienced an oscillation as illustrated in the chart.

Figure 5 shows the oscillating crest and trough magnitudes of active and reactive power due to additional loads on seconds of 8, 12, 16 and 20. The oscillating

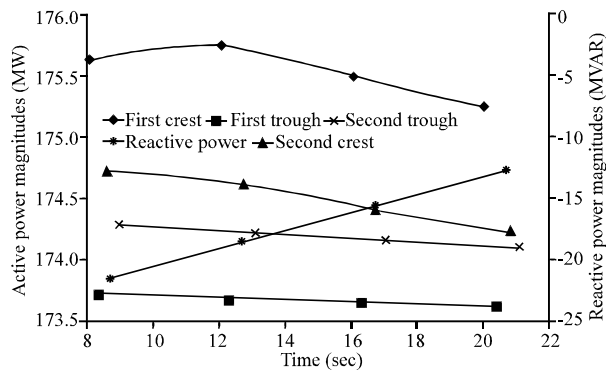


Fig. 5: Oscillating magnitudes of active and reactive powers

magnitudes tended to decrease as the second of additional loads increased. This case was occurred significantly enough, especially, for the first crest and first trough. This case was also, occurred on the second crest and the second trough of oscillating waves but not so, significant. These occurrences were also, applied for the reactive power ones, however, they were in negative values. Therefore, it was more resistant to the additional loads on the system due to the power in the system would be greater than the previous ones.

Figure 6a describes the speed graph of the generator 1 for 25 sec in which there were the additional loads at the second to 8, 12, 16 and 20 with each rise level as 25% of 175 MW and 85 MVAR. From the figures, it can be seen the starting oscillation occurs because the generator seek a balance in the face of infinite bus. The oscillation itself was occurred the starting for 7 sec from second 0-7, in which the maximum amplitude was equal to around 336.88 rpm. Nevertheless, it was still within safe limits generator. For this condition, there were small oscillations due to additional load on the network 500 kV. One of effects of the minor disturbance was an oscillation in the generator rotor angle which can be shown in Fig. 6b. It shows the oscillations in the generator, either when starting or due to the additional load. When starting, its own oscillation occurs were the minimum of -37.28° and -27.51° of first and second values, respectively where the oscillation occurs during 7 sec. This case was due to the current system was beginning to adjust to the balance of infinite bus system. The rotor small angle oscillation was also, experienced due to the load additions.

Figure 6c describes the magnitude of the voltage on the terminal and bus for the generator 1. When starting, the system voltages were experiencing the oscillations for 7 sec. The oscillations would closer occur during the second of 0-0.08 because like as the previous section that the system adapted to the load condition or in this case,

the infinite bus. The greatest amplitudes were occurred in seconds to 0 as 17.1 kV and 540.7 kV for the terminal and bus voltage, respectively. When there were the additional loads at the seconds to 8, 12, 16 and 20, the voltage oscillations were also occurred, although, smaller compared to the starting conditions. The terminal voltage tent to be constant, closed to 16.5 kV. Nevertheless, the bus voltage tended to decrease due to the additional loads to the nominal voltage of 500 kV. The voltage on the system should be kept as the constant value, so that, the expected changes were not significantly influenced by the changes of power.

Figure 7 shows the synchronizing constant, damping constant and oscillating frequency charts of generator 2 due to additional load at second of 8. It is shown that the synchronizing and damping constants were relatively constant. The rotor oscillating frequency would vary slightly due to additional loads.

The oscillation due to the load addition was not too large because the voltage must be kept to its reference of infinite bus. The highest signal voltage amplitude at the second of 8.55 as 0.9997 pu or 16.494 kV. While the time required returning to the steady state was 1.3 sec.

Actually, the phase angle due to the load addition did not change significantly because basically, the power factor for this system on the network was constantly kept, so that, the angle did not change too. The smallest voltage, phase angle was at 8.3 sec as 9.057° and the highest one as 9.16° . Thus, the difference between the largest and smallest angles was 0.103° . The terminal voltages for both generators and both starting and oscillating conditions were same, due to both generators were identical.

The E_b bus voltage oscillating chart was occurred when the starting because the system searched for the appropriate voltage to the condition on the infinite bus. The oscillation was also, occurred when there was an additional load, however, it was not too significant. This phenomenon could be attributed to the system that would keep E_b voltage remained constant, since, the voltage was the reference to be kept. The oscillation was occurred when starting for 3 sec from 0-3 sec with the dense oscillation was occurred during 0.08 sec with the maximum amplitude of 1.03 pu or 540.8 kV. When there was an additional load, it would yield the oscillation from 8-9.3 sec or during 1.3 sec.

Nevertheless, that interesting one, it was occurred small voltage drop of 0.001 pu or 500 V, due to the load addition. The phase angle bus voltage of 500 kV did not change significantly due to the load addition because the power factor was kept to be constant. This was evidenced

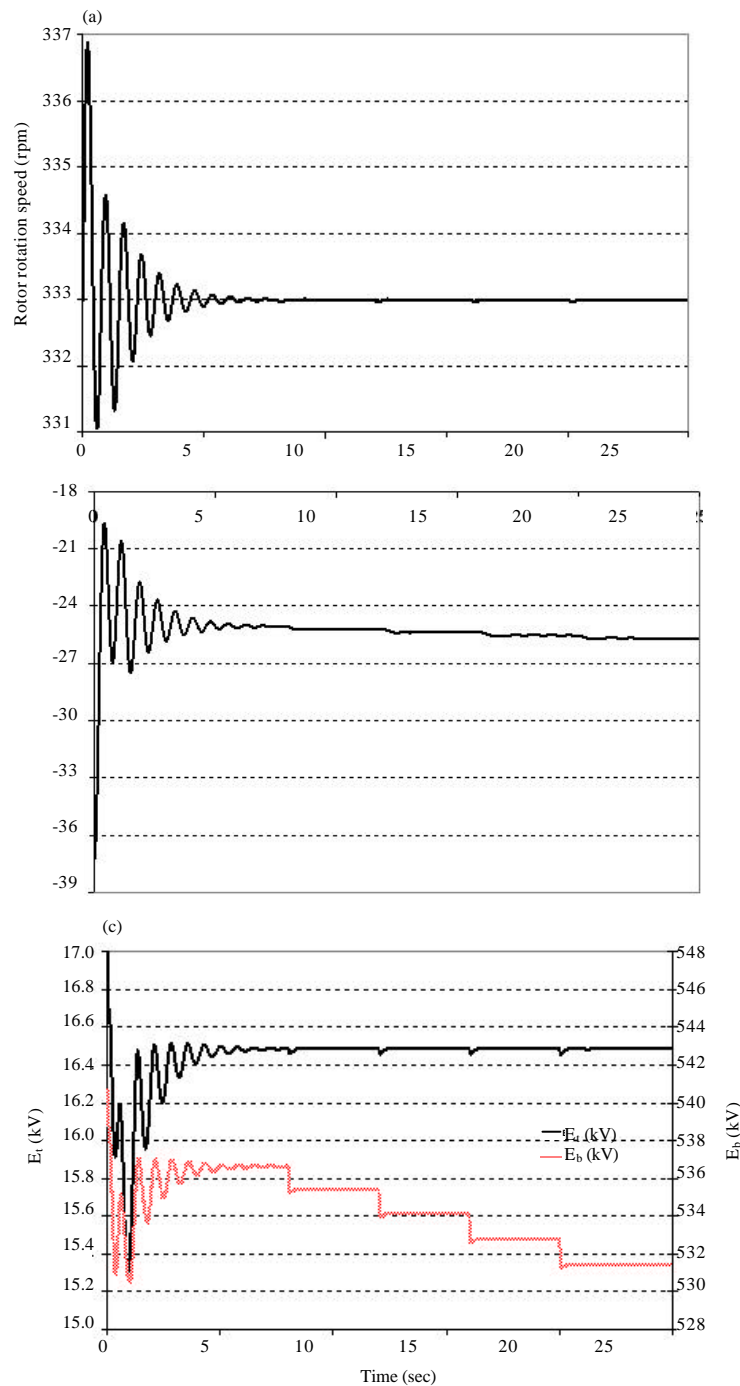


Fig. 6: a) Rotor rotation speed; b) Rotor angle and c) Terminal and bus voltage charts

by the smallest angle of 30.29° at 8.25 sec and the largest angle of 30.38° at 8.00 sec. Thus, the difference between the largest and smallest angles was 0.09° .

The speed chart of the generator 1 was one of the parameters that the system was whether stable or not. It could be seen from the rotation generator when in the face

of large system or fault. In this case, it was the addition of load on the network system of 500 kV, 175 MW and 85 MVAR. The oscillation for the starting occurrence within 3.5 sec from zero to 3.5 sec in which the maximum speed was equal to 1.008 pu or 335.7 rpm. Where, it was still within safe limits.

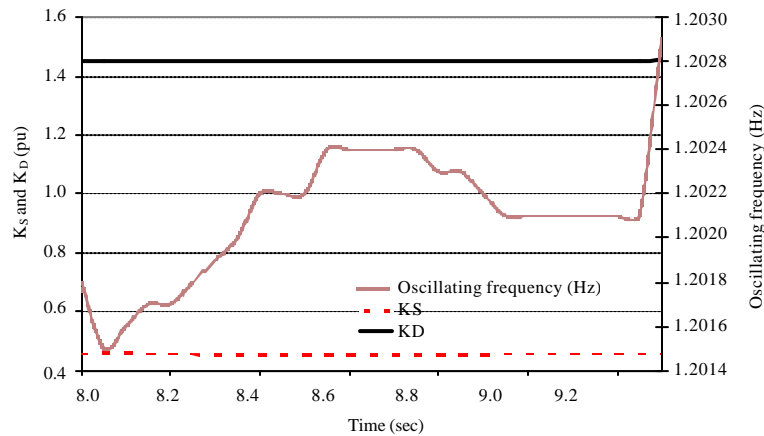


Fig. 7: Synchronizing constant, damping constant and oscillating frequency charts of generator 2 due to additional load at second of 8

Table 3: Synchronizing and damping constants and oscillating frequency

t (sec)	K_s (pu)	K_d (pu)	Oscillation frequency (Hz)
8.00	1.4771	0.5368	1.2121
8.05	1.4732	0.5395	1.2015
8.10	1.4735	0.5365	1.2017
8.15	1.4737	0.5336	1.2108
8.20	1.4738	0.5316	1.2108
12.00	1.4779	0.5277	1.2125
12.05	1.4779	0.5321	1.2125
12.10	1.4751	0.5293	1.2113
12.15	1.4758	0.5261	1.2113
12.20	1.4757	0.5239	1.2116
16.00	1.4797	0.5190	1.2132
16.05	1.4761	0.5229	1.2117
16.10	1.4766	0.5205	1.2119
16.15	1.4772	0.5175	1.2122
16.20	1.4780	0.5149	1.2125
20.00	1.4814	0.5103	1.2139
20.05	1.4778	0.5137	1.2124
20.10	1.4783	0.5115	1.2126
20.15	1.4788	0.5090	1.2128
20.20	1.4796	0.5067	1.2132

Because the load addition, the generator should supply more power than the previous one and lead generators must achieve the appropriate rotation speed, so that, the power could be well supplied and the speed of generator back to its steady state at the second to 9.3. The generators of 1 and 2, in this simulation were identical, so that, the speed of generator rotor was the same when both starting and oscillation.

In the calculations of small signal, it would be divided into several periods based on the oscillation chart. As a reference of small signal stability, the calculations on the initial conditions were done immediately before the load addition, in this case, in the second to 7.8. Then, it was resumed, when the power calculation was having the oscillation during the additional load of 175 MW and 85 MVAR on the 500 kV network. The testing with this load was based on the notion that small-signal stability was

the ability of plant to maintain stability against small disturbances where the minor annoyances were disorders that could be linearized. The amount of additional load of 175 MW based on the ability of generator nameplate as 206.1 MVA with 0.85 pf lagging, so that, it was obtained 175 MW of power. Based on these data, the ability of current generator should be able to supply the infinite load bus and then there was the additional load. By effects of the load oscillations, there were evident from the charts of the figures, it could be expressed as minor nuisances because the minor disturbances could be changes of load, on the load or generating side in random, slow or fall-rise with its influence on the power flow was not significant.

As the samples on the results of eigenvalues, the second and third eigenvalues were complex numbers with a value of $-0.0286+7.5481i$ and $-0.0285-7.5481i$ where the real numbers stating the magnitude of damping in the system while the imaginary values were associated with the magnitude of damped oscillation frequency in the system when an increase in amplitude of oscillation. It could be determined the magnitude of damping ratio ζ as 0.0038. The damping ratio determined the amount of deficiency or amplitude anomaly when an oscillation occur. It was also, obtained magnitude of the oscillation frequency to identify the problems in the mode of second to 7.8 as 1.2013 Hz. From these results, it could be stated that the problem were inter-machine or inter-plant mode oscillations.

To determine the synchronization and damping constants of the system those were influenced by the excitation system and PSS, it was required calculation analysis of each component with $s = -0.0285+7.5481i$. The synchronization constant was influenced by the

magnitude of phase angle difference and the attenuation constant helped system to remain at actual speed. It meant the two components helped the system to stay in synchronous state during the change of phase angle and helped damping the speed of oscillation system.

Table 3 lists the part of generator oscillating data for calculation of small-signal stability those are indicated by the synchronizing constant, damping constant and the oscillating frequency. The obtained oscillation data were sampled every 0.05 sec. Based on the samples, the first times, seconds to 8, 12, 16 and 20, the values of K_s and oscillation frequency would rise as the time increased. Otherwise, it was vice versa for K_D . Nevertheless, the system was still in stable condition.

By the magnitude of current oscillation frequency, the problem could be identified as intermachine or interplant mode oscillations. By the addition of load in increments of 25% of 175 MW and 85 MVA at the seconds to 8, 12, 16 and 20, they were resulting in the differences of K_s , K_D and the oscillating frequency. This was caused by every system change was always looking for a new balance point. The oscillation frequency would increase as the synchronizing and damping torque coefficients increased, although, not exhibited significantly. It could be associated with the shape of the signal oscillations were almost the same but the magnitudes were different. Thus, each phase load increased, K_s and K_D also, went up to be able to keep the machine in synchronous condition and able to damp the oscillation speed. It meant the two components, AVR and PSS, helped the system to stay in synchronous condition during a change of phase angle and helped to damp the oscillation due to a speed change.

CONCLUSION

The disturbance in the simulated small signal applications with load testing out its entry on the second to 8 for 175 MW+j 85 MVAR, resulting oscillations in active power, reactive power, voltage terminal, rotor speed and rotor angle on each generator, so, even with infinite voltage on the bus for 1.3 sec. The charts were generated from both machines as the same due to identical characteristics. From the tests, it was known that the asymptote in the state of stable because based on the calculating results that the system had negative real eigenvalue for each condition. The faced problems were intermachine oscillations or the circumstances in which the two generators oscillated in one area with the oscillation frequency range between 1.2108-1.2132 Hz. When compared to previous additional load, the system had the oscillation frequency of 1.2 Hz which meant that

it was smaller than that when the load addition. This case could be overcome by the AVR and PSS, in this test provided the synchronization and the damping constants as 1.47 and 0.50 pu of speed change, respectively. The damping ratios of the system based on the calculations were obtained as 0.0043-0.0044.

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