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Stability Study of a 23 MVA Turbine Generator

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Abstract

Power system stability is a very important issue in power system engineering because a decrease in the stability margins can cause unacceptable operating conditions, which leads to frequent failures. In this paper, SKM POWER TOOLS PTW-32 Version 4.5.2.0 was used to study different Stability recovery tests after a medium voltage short circuit fault on a turbine generator in the power system. The analysis focused on the generator electrical and mechanical powers stability recovery test, generator speed stability recovery test, excitation voltage stability recovery test, bus voltage and bus frequency stability recovery test. In our study, when the introduced fault was cleared after 0.5 s, it reveals that the recovery rate of electrical power was much faster than that of mechanical power. Also, the results reveal that it took about 10 seconds for the turbine speed to stabilize while it took fewer seconds for the frequency to stabilize.

Keywords

Power System Stability, Turbine Generator, Power System Limit

1. Introduction

1.1. Power System Stability

Generally, stability can be said to be the ability of a system to regain its original equilibrium state after a disturbance [1]. Therefore, power system stability is now defined as the tendency of the power system to restore its initial position after a disturbance [2]. It is observed that the power system stability margin is decreasing due to mainly economic considerations.

Stability can be categorized into three groups that are transient, dynamic and steady state stability [3]. Transient stability is regarded as a type of stability pattern that is beyond linear and continuous control capabilities. On the other hand, dynamic stability is a sudden and small disturbance and can be stabilized by linear and continuous stability control while steady state stability is a type of stability that occurs as a result of a sudden and relatively small disturbance as a result of sudden changes in load. The stability of the power system is critical because the decrease in the stability margin beyond a certain level can cause unacceptable operating conditions including frequent failures. According to [4], a stability margin situation of this nature can be controlled using adaptive control devices which can prevent unexpected failures and cascading sequences of events. For a steady state situation, the mechanical input power balances out the electrical power output. The mechanical input power is the product of speed and torque, and it moves in the direction of rotation while the electrical torque moves in the reverse direction [5]. The average electrical power is equal to the mechanical power. Therefore, if there is a disturbance in the system, a parameter of the electrical power equation is changed [6]. Stability issues have attracted a lot of attention in recent times with emphasis on control, planning and operation of the system. The issues of the power system are raising a lot of concern with increasing demand for power and loading of the transmission system.

In this paper, the stability of a 23 MVA turbine generator is investigated. The investigation is centered on the mechanical power recovery test, speed recovery test, frequency recovery test and excitation voltage recovery test.

1.2. Power System Stability Analysis

Under steady state conditions, the mechanical power input balances the electrical power output. The electrical torque and mechanical torque move in the opposite direction; that is, the mechanical torque moves in the direction of rotation while the electrical torque moves in the opposite direction [5] as shown in **Figure 1**.

The product of the speed and torque can be said to be the mechanical power and electrical power of the generator as depicted in Equations (1)-(3).

$$P_m = \omega T_m \tag{1}$$

where, ω = angular velocity, P_m = mechanical power, T_m = mechanical torque.

$$T_m - T_e = T_a \tag{2}$$

where, T_e = electrical torque, T_a = accelerating torque.

If $T_m = T_e$, then $T_a = 0$, meaning there is no angular acceleration and the machine is in synchronism.

The electrical power of the generator is also a product of electrical torque and the speed of the unit,

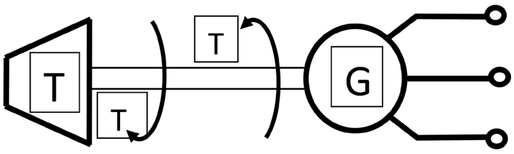


Figure 1. Mechanical and electrical torque applied to a generator shaft.

$$P_e = \omega T_e \tag{3}$$

Following a disturbance, the change in electrical torque can be resolved into two components,

$$\Delta T_e = K_s \Delta\delta + K_D \Delta\omega \tag{4}$$

where, $K_s\Delta\delta$ = a component of the torque in phase with the rotor angle change. $K_D\Delta\omega$ = a component of the torque in phase with the speed change.

The average mechanical power must be equal to the average electrical power, P_e. When a disturbance occurs in a system, there is a change in one of the parameters of the electrical power equation [6].

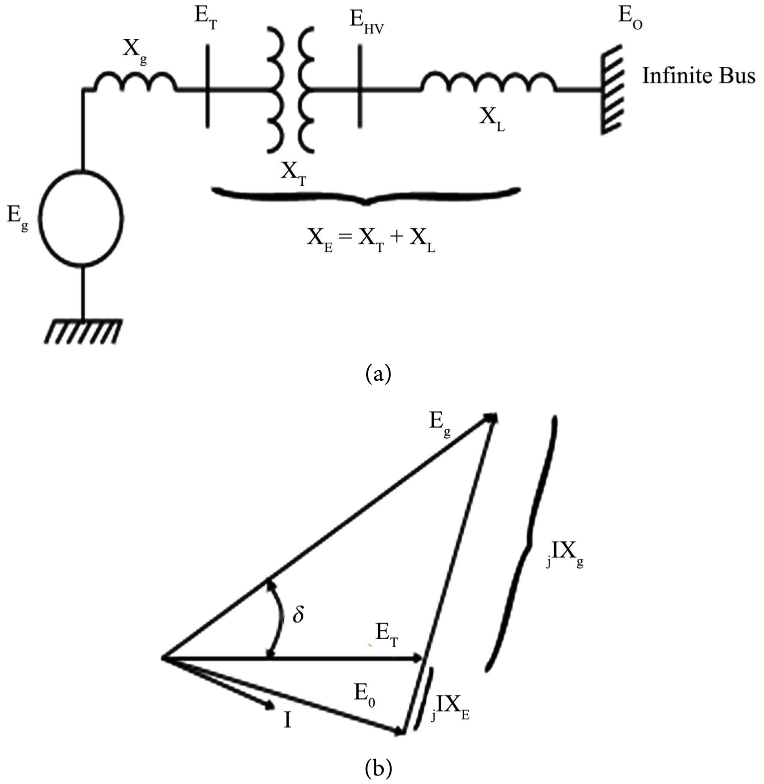
$$P_a = P_m - P_e \tag{5}$$

where, P_e = Electromagnetic power output, P_m = Mechanical turbine power of the generating unit, P_a = Accelerating power.

The real (MW) power output from the generator to the load is given by the equation. **Figure 2** shows the generator tied to an infinite bus.

$$P_e = \frac{E_g E_T}{X_g}\sin\delta \tag{6}$$

where, EHV = Extra High side voltage, E_T = Generator terminal voltage, X_g = Generator internal reactance E_g = Internal generator voltage, X_E = External impedance, E_O = System voltage. δ = angle that the Internal Voltage leads the Load Voltage.



(a)

(b)

Figure 2. (a) Generator tied to an infinite bus; (b) Phase diagram.

Electrical generators are driven by prime movers that are equipped with closed-loop control systems. The closed loop system is used to decrease the shaft speed over the full range of the shaft power. The speed deviation in this case is then used to operate the fuel valve so as to reduce the speed deviation [7]. The power system is usually occasioned with large disturbances as a result of faults and line switching. A system that cannot survive initial disturbance is regarded as transiently unstable while a system that can survive is a transiently stable system. When a large disturbance occurs in a transiently stable, the angle speed increases until it reaches the peak, then it will start to decline making the system to be transiently stable. Transient stability of the system can only occur when it is able to withstand the transient condition after a large disturbance [4]. Load performance in the presence of a disturbance is a concern in power system planning and operation [8].

2. Review of Related Literature

In engineering, stability is a very important and fundamental concept in a power system. It can be divided into three categories, namely frequency, voltage and rotor angle stability. The reason for the classification of stability is to aid analysis because different techniques are used to analyze the causes and symptoms of a disturbance. The different types of stability can be further grouped into large and small disturbances. Due to the fact that stability is a major issue in power system, and can instability in dynamic system, many researchers have defined stability in different ways. According to [9], the stability of a system is regarded as the tendency of the system to return to its equilibrium state after a disturbance by developing restoring forces that are greater than the disturbing forces. Reference [2] hints that a system can be regarded as stable if it is able to return to its initial equilibrium position. In reference [8], power system stability can be said to be the ability of the electric power system to regain its initial operating equilibrium after a disturbance.

The power system power is generally affected by faults that result in power loss. To bring a system back to its original operating state, a corrective measure must be considered to bring the system back to stability. Due to the complexity of the power system, the dynamic of the system can be impacted by different response rates and characteristics. The instability of the power system can occur in different ways depending on the mode of operation and the system topology [9] [10].

Power System Limits

For a system to be reliable, the system must operate within its power transfer limits. The limits place a constraint on the generated and transmitted power (that is the active and reactive power) and it is divided into voltage and thermal limits.

Thermal limit

This type of limit affects the power system equipment's thermal capabilities because when power and current in the system increases, it can damage the equipment. Operating equipment beyond its maximum operating limit in the power system can result in thermal damage, and the damage can occur in the stator or rotor windings.

In the transmission system, all associated equipment must operate within their thermal limit because the excess current in the system can cause the overhead line conductors to sag thereby reducing ground clearance and the safety margins. A very high current within the system can damage the metallic structure of the overhead conductors causing sag. For underground cables, it must depend on the insulation to dissipate the generated heat. Overloading equipment will result in damage or loss of service life. It is advisable to avoid the safe overloading of power system equipment because we can tell how much the overload is.

Voltage limit

Voltage limit is very important; that is why customers and power system equipment are designed to operate within a certain voltage standard. A large deviation from the rated or nominal voltage limit can cause system failure or serious damage. In some cases, an unacceptable voltage drop is observed at the end of a transmission line due to large reactive losses as current flow through the system. Also, if the system generator is unable to produce the reactive power to meet the system.

A system can produce less active power as expected if the system does not have enough reactive power reserve to support the system voltage.

Stability limit

The stability of a system is regarded as the ability of a system to return to its equilibrium state after a disturbance. Also, the instability of a system can because by the operating condition/mode and topology/configuration of the system. Synchronism of the system is also a major cause of instability. We can say that this kind of stability is influenced by the rotor angle of the generator.

Rotor angle stability is very important because it allows the power angle and system torque to remain controllable. The system torque and power cannot be controlled if the rotor angle is unstable because when there is a major disturbance, a system operator can easily lose the ability to control the system.

Figure 3 shows the plot of the power angle curve. The plot shows the power transfer between two buses when the power angle is varied. The plot shows that the maximum power transfer is achieved when the angle between two buses is 90˚. Also, the power transfer can be increased when the angle spread increases. When the angle is 90˚, more power is transferred out of the generator than mechanical power, thereby causing the rotor angle and frequency to decrease. Also, when the rotor angle decreases, power will now be injected into the generator than will be transferred out. This action will accelerate the rotor angle and increase the system frequency. The rotor angle spread only when there is a deceleration or acceleration [10] [11] [12] [13].

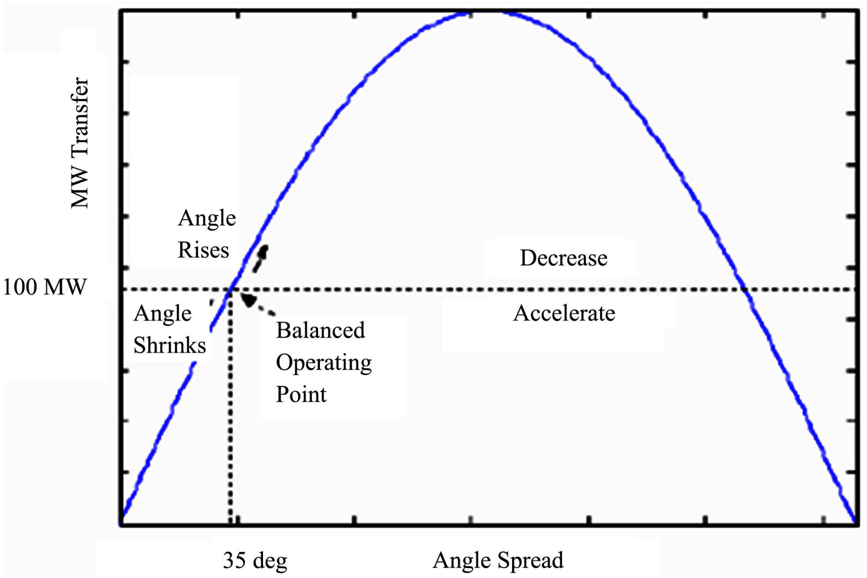


Figure 3. Power angle curve.

3. Materials and Method

3.1. Materials

The materials deployed in these investigations are hardware, software and data of hardware materials. The hardware materials are turbine driven main power generator of 23 MVA capable of being synchronized locally or remotely for parallel operation, a diesel-engine-driven generator of 69 MVA capable of being synchronized to the main generators such that they operate in parallel and share loads and finally, the emergency power generator of 1.4 MVA where simulations were carried out and capable of being synchronized to the main generator.

The software applications used in the simulations are:

1) SKM Power Tools for Windows (Version 4.5.2.0);

2) Power Tools for Windows, (Version 4.5.2.5);

3) Transient Motor Starting module (TMS).

3.2. Data Used for the Simulation

Tables 1-7 were used for the simulation and investigation of the stability of the turbine generator data. The data used are from the generator automatic voltage regulator (AVR), and a power transformer.

3.3. Method

After the setup and installation of the software alongside data collection into the system for simulation, a connection was established between the generator control panel and computer using the Recommended Standard 232 data cable. On successful completion of this, simulation results were generated by the software and some plots were obtained.

Table 1. Generators input data.

S/N	GEN Name	Gen Number	Rated Power (Kw)	Rated Voltage (V)	X"d (pu)
1	Turbine Gen	IZAN-83331	23,000	11,000	0.2
2	Turbine Gen	IZAN-83364	23,000	11,000	0.2
3	Turbine Gen	IZAN-83297	23,000	11,000	0.2
4	Essential Gen	IZAN-83269	5200	6600	0.1
5	Emergency Gen	IZAN-83101	1400	400	0.1

Table 2. Power transformers input data.

S/N	Transformer Tag Number.	Nominal Capacity (kVA)	Primary Voltage (V)	Secondary Voltage (V)	Percentage Impedance
1	1TR-MV01A	25,000	11,000	11,275	6.5
2	1TR-MV01B	25,000	11,000	11,275	6.5
3	1TR-MV02	1000	11,000	11,000	5.57
4	1TR-MV03	1000	11,000	11,000	5.57
5	1TR-MV04	2000	11,000	11,275	5.79
6	1TR-MV05	2000	11,000	11,275	5.79
7	1TR-MV06	2500	11,000	11,000	6.06
8	1TR-MV07	2500	11,000	11,000	6.06
9	1TR-MV09	2500	6600	6600	5.94
10	1TR-MV010	2500	6600	6600	5.94
11	1TR-MV011	1600	11,000	111,275	5.75
12	1TR-MV012	1600	11,000	11,275	5.75
13	1TR-MV013	2500	11,000	11,550	6.06
14	1TR-MV014	1600	11,000	11,000	5.72
15	1TR-MV01A	8000	11,000	11,275	6.63
16	1TR-MV01B	8000	11,000	11,275	6.633
17	1TR-MV02A	800	6600	6765	5.75
18	1TR-MV02B	800	6600	6765	5.75
19	1TR-MV08	2000	6600	6765	5.75

Table 3. Power Transformers tap positions/settings.

S/N	Transformer Tag Number.	Nominal Capacity (kVA)	Nominal Primary Voltage (V)	Real Primary Voltage (V)
1	1TR-MV01A	+2.5	11,000	11,275
2	1TR-MV01B	+2.5	11,000	11,275

Continued

3	1TR-MV02	0	11,000	11,000
4	1TR-MV03	0	11,000	11,000
5	1TR-MV04	+2.5	11,000	11,275
6	1TR-MV05	+2.5	11,000	11,275
7	1TR-MV06	0	11,000	11,000
8	1TR-MV07	0	11,000	11,000
9	1TR-MV09	0	6600	6600
10	1TR-MV010	0	6600	6600
11	1TR-MV011	+2.5	11,000	111,275
12	1TR-MV012	+2.5	11,000	11,275
13	1TR-MV013	+5	11,000	11,550
14	1TR-MV014	0	11,000	11,000
15	1TR-MV01A	+2.5	11,000	11,275
16	1TR-MV01B	+2.5	11,000	11,275
17	1TR-MV02A	+2.5	6600	6765
18	1TR-MV02B	+2.5	6600	6765
19	1TR-MV08	+2.5	6600	6765

Table 4. Exciter parameters of the main power generator.

Symbol	Description	Value
Vr	field voltage (1 p.u)	13.8 (V)
RF	Exciter field resistance	6.0 Ω
EFD	Exciter output voltage (1 p.u)	21.2 (V)
TE	Exciter field time constant	0.32 sec
KE	Exciter constant	1.00
SE (E1)	Exciter saturation function at 100% ceiling voltage	0.64
E1	75% ceiling voltage	6.9 pu
SE (E2)	Exciter saturation function at 100% ceiling voltage	0.81
E2	100% ceiling voltage	9.2 pu
EFD	Rotor voltage at full load	92 V
IFD	Rotor current at full load	944 A

Table 5. AVR parameters of the main power generator.

Symbol	Description	Value
KP	Field proportional gain setting	401

Continued

KI	Field integral gain setting	1
KD	Field differential gain setting	9104
TA	Amplifier time constant	0.00153
TD	Differential Constant	0.00 sec
Tr	Input filter time constant	0.03 sec
VrMax	Maximum regulator output voltage (p.u)	0.01 sec
VrMin	Minimum regulator output voltage (p.u)	10.9 pu
E2	100% ceiling voltage	0 pu

Table 6. Main power generator model.

Symbol	Description	Value
Ra	Armature resistance, the typical range is 0.0 < Ra < 0.01	0.002 Ω
X_d	D-axis armature reactance (p.u)	2.22
X_q	Q-axis armature reactance (p.u)	1.1
X_d'	D-axis transient reactance (p.u)	0.37
X_q'	Q-axis transient reactance (p.u)	1.099
X''	Machine sub-transient reactance (p.u)	0.215
XI	leakage reactance (p.u)	0.10
H	Inertial time constant of the shaft and turbine	1.54 $kg/m^2 \cdot s$
D	load damping coefficient	0
$T_{d0'}$	d-axis open circuit transient time constant	12.1 sec
$T_{d0''}$	d-axis open circuit sub transient time constant	0.06 sec
$T_{q0'}$	q-axis open circuit transient time constant	0.2 sec
T_{q0}''	q-axis open circuit sub transient time constant	0.06 sec
S_{10}	Saturation factor at a voltage = 1 p.u	0.15
S_{12}	Saturation factor at a voltage = 1.2 p.u	0.46

Table 7. Essential power generator model.

Symbol	Description	Value
Ra	Armature resistance	0.002 Ω
X_d	D-axis armature reactance (p.u)	0.72
X_q	Q-axis armature reactance (p.u)	0.54
X_d'	D-axis transient reactance (p.u)	0.35
X''	Machine sub-transient reactance (p.u)	0.062
XI	Leakage reactance (p.u)	0.072

Continued

H	Inertial time constant of the shaft and turbine	2 kg/m^2·s
D	Load damping coefficient	0
$T_{d0'}$	d-axis open circuit transient time constant	5 sec
$T_{d0''}$	d-axis open circuit sub transient time constant	0.05 sec
$T_{q0}^{''}$	q-axis open circuit sub transient time constant	0.06 sec
S_{10}	Saturation factor at a voltage = 1 p.u	0.11
S_{12}	Saturation factor at a voltage = 1.2 p.u	0.48

The following stability test measurement was taken during the research:

1) Stability tests when starting one 11 kV induction motor;
2) Stability tests on the loss of one of two main generators without load shedding;
3) Stability tests on the loss of one of two main generators with load shedding;
4) Stability tests on tripping of one of three Turbine Generators;
5) Stability tests on the loss of the Essential Generator;
6) Transient motor starting tests under Essential Generator configuration;
7) Transient motor starting tests under Emergency Generator configuration;
8) Stability recovery after medium voltage (MV) short circuit fault.

4. Results and Discussion

In this study, five different Stability recovery tests after medium voltage short circuit fault were plotted against time and analyzed. They are the generator's electrical and mechanical powers, generator speed, excitation voltage, and bus voltage and bus frequency test.

The mechanical power of one generator before the short circuit fault was about 10,000 kW. When the fault occurred, a very high amount of current was involved, the mechanical power of the engine dropped considerably below zero. Within a period of 0.5 seconds, the fault cleared and the mechanical power shot above 17,500 kW but finally stabilized at the initial value of 10,000 kW within 10 seconds from when the fault occurred. The electrical power stabilized within fewer seconds after the fault as shown in **Figure 4**. These graphs also show that after the short circuit fault the recovery rate of electrical power was much faster than that of mechanical power. This agrees with the submission of [14] [15]. Here, the electrical power recovered within 0.5 seconds while the mechanical power took as much as 10 seconds before it could fully recover.

The short circuit fault affected both the speed of the turbine and the frequency of the generated voltage. It took about 10 seconds for the turbine speed to stabilize while it took fewer seconds for the frequency to stabilize as depicted in **Figure 5**. The excitation voltage was equally affected as the short circuit fault caused the bus voltage to dip and so the AVR called for an increase in the excitation voltage so as to overcome the voltage dip, as shown in **Figure 6** and **Figure 7**. This explains why the excitation voltage initially shot up to about 400% of the

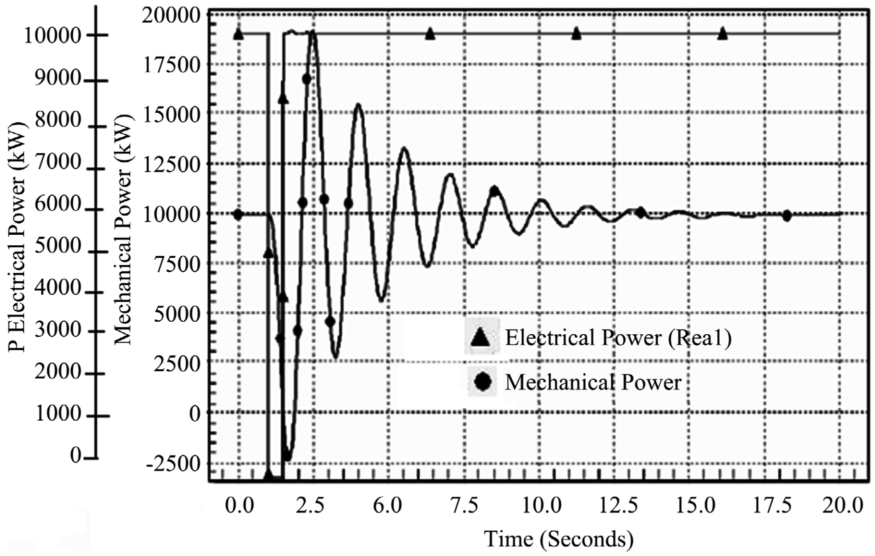


Figure 4. Variation generator mechanical and electrical power with time.

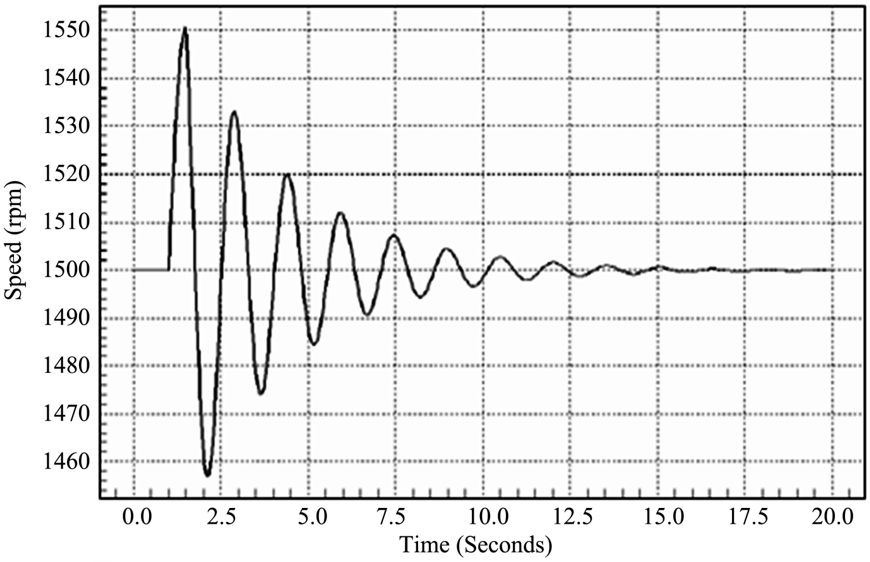


Figure 5. Stability recovery of turbine generator speed.

pre-fault value. It later reduced and stabilized within 8 seconds after the fault. The bus frequency initially shot up to 51.7 Hz but soon reduced to 48.5 Hz and fluctuated for more seconds before it finally stabilized at its nominal value of 50 Hz after about 10 seconds as shown in **Figure 8**.

The initial increase in the excitation voltage was a result of the dip in the generator voltage within the same time frame. These results are in concord with the submission of [16]. However, in **Figure 8**, the frequency first shot higher than the nominal value before going low and finally stabilized after 8 seconds. The expectation here, as given by [16] is that the frequency should first go low during the fault and then spike to a higher value after the fault has been cleared before it finally recovers and stabilizes.

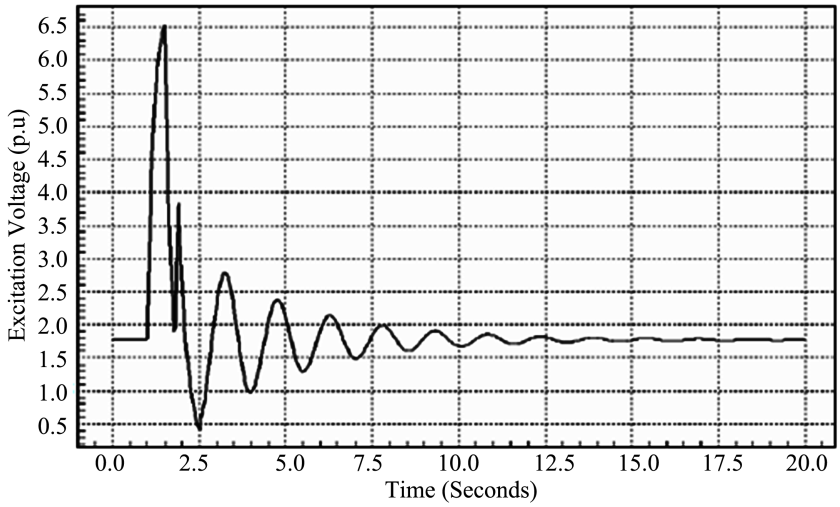


Figure 6. Stability recovery of turbine generator excitation voltage.

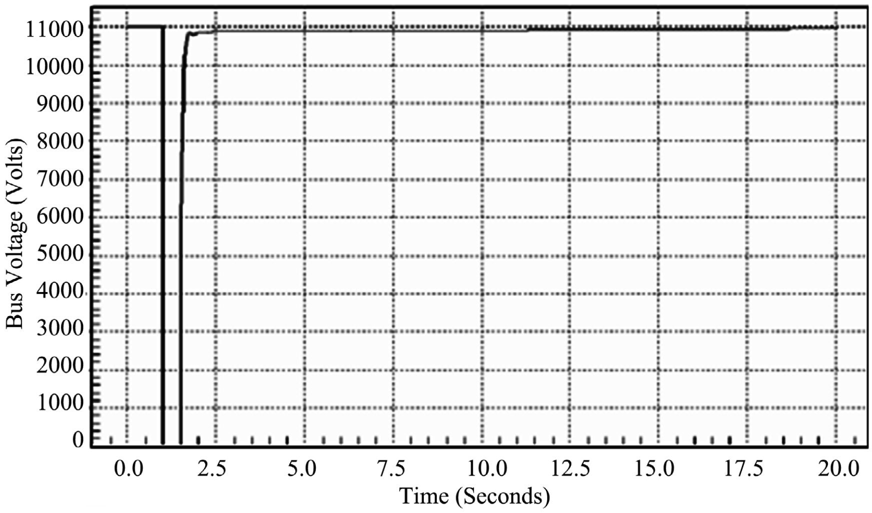


Figure 7. Stability recovery of turbine generator 11 kV bus voltage.

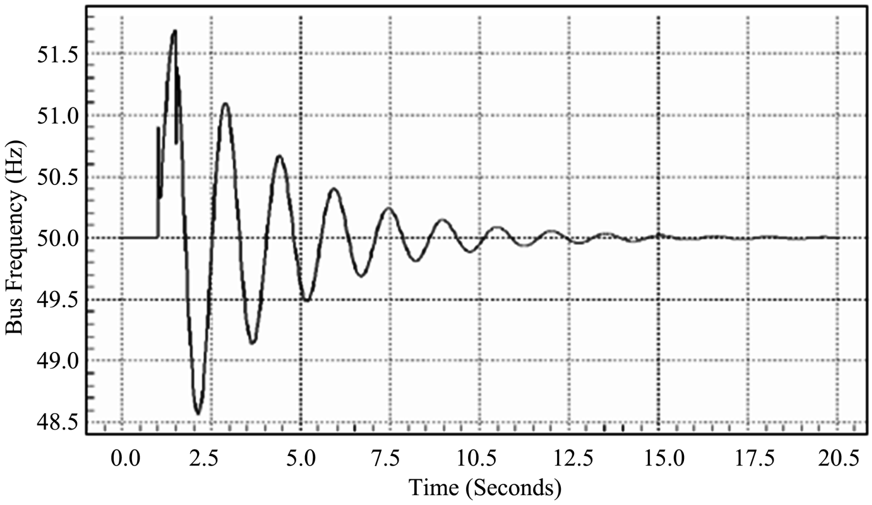


Figure 8. Stability recovery of turbine generator 11 kV bus frequency.

5. Conclusion

Stable electric power systems are achievable when the elements and devices that influence such power systems are effectively controlled. The dimension and complexity of the system determine the control philosophy and implementation based on the chosen control dynamics. Control therefore remains a sure means to attain, enhance and sustain transient stability in large power systems. In the transient motor tests conducted and measurements taken, it was seen that whenever heavy loads were started up, there were reductions in the bus-bar voltages from the pre-startup values. The initial currents the loads drew from the system during start-up were much more than the currents required to keeping the motors running once they attained full speed. This also affected the generator speed as it initially slowed down. Also affected were bus frequency, the real and reactive powers from the generator as well as the mechanical power from the turbine engine. These show that the transient stability of a power system depends not only on the overall capacity of the system but also on the total loads connected to it as well as the electrical "weight" of the individual loads.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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