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Determination of Effective Load Shedding Schemes in Electric Power Plants

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Abstract

The ability of power system to survive the transition from preloading state to the gradual increase in load and thereafter reach an acceptable operational condition is an indication of transient stability of the system. The study analyzed load shedding scheme through the use of empirical measurement tools and load-flow simulation techniques. It was geared towards determining effective load shedding strategies to reduce unnecessary overload in order to achieve dynamic stability of the electric power network in the Export Free Trade Zone, Calabar, Nigeria. From the tests and the measurements taken, it was observed that the real and reactive powers from the generator and the mechanical power from the turbine engine were stable when the load shedding controller was switched on, as compared to when it was off. The engine speed, the bus-bar frequency and the output voltage of the generator stabilized within a shorter time (about 8 seconds) when the controller was switched on than when it was on the off condition. Also, there were noticeable fluctuations in the speed of the remaining two generators. It became stable at about 12 seconds after the loss. The variations were 0.3 per cent of the nominal speed value. The excitation voltage fluctuated from 1.2 (pu) to 4.5 (pu) when the bus voltage dipped as a result of additional load. It then came down and stabilized at 1.8 (pu) after few swings. This confirmed that the stability of power system is much enhanced when load shedding controllers are effectively configured on the network.

Keywords

Power System, Transient Stability, Load Shedding Scheme, Electric Power Network

1. Introduction

1.1. Load Shedding System

Design of Power systems is usually tailored towards key parameters that can aid effective and efficient operation; in line with the anticipated contingencies. One of such key indicators is load-shedding. However, in practice, there are cost-effective strategies to tactically arrest unforeseen events that may lead to outages. Major design parameter under which a system may be designed to operate satisfactorily is load-shedding. Processes are usually put in place to check rare conditions where the capacity of the system can be exceeded. Such processes can automatically monitor the loading levels of the power system in order to reduce loading when required. Under real-time operation, it may become expedient to prioritize the loads so as to readily determine those to switch off whenever there is a diminution in generation or a disorder in the system. This practice is referred to as *load shedding* [1].

The load shedding structure robotically senses overload conditions and sheds the intemperance load to relieve the overloaded power system network before there is failure of generation, line tripping, equipment damage, or a chaotic random shutdown of the system. Overloads may be separately viewed using two scenarios [1]:

1) Operating systems in which there is a real power deficiency and in the inability of the prime mover torque meets the load torque, thereby forcing the generation to decelerate. This scenario can be manifested as the voltage drops and the transformer's reactance prevents power delivery to loads.

2) Another form of overload is by the magnitude and suddenness of the overload condition. Under this scheme, the overload condition arises and progresses rapidly; whereby the condition cannot be sustained when a high speed automated response is required.

1.2. Method of Detection and Response of Overload

This method requires frequency, voltage or supervisory control and data acquisition (SCADA) monitoring. Automated load shedding systems are necessary for industrial power systems since sudden disturbances can plunge the system into a hazardous state much faster than an operator can react. These automated schemes must be designed and implemented to possess in-depth knowledge of system operating parameters, and must rely on time-sensitive monitoring and control communication networks in order to achieve the desired outcome of fast and optimal load shedding at the onset of a disturbance [2]. There are three conditions upon which load shedding can occur.

1) *Load shedding upon generator loss*: When there is loss of one or more generators due to a major fault, there will be power deficit; that is, the available power will be less than the required power [2]. This is demonstrated in Equation (1):

$$P_{di} = G_i \left\{ P_i - G_i \left(P_{ci} - P_i \right) \right\} + P_{sri} \tag{1}$$

where,

i = Index value of the generator (internal data)

G_i = 1, if generator is connected to sub-network; 0 if not connected

P_{di} = Power deficit on loss of generator i

P_i = active power delivered by generator i

P_{ci} = Power capacity of generator i

P_{sri} = Power reserve (spinning reserve) on sub-network i

2) *Load shedding upon under-frequency*: When there is an under-frequency condition from any of the generators, the average frequency of the system does not decay instantly. Rather, the stored rotational energy of the generator is absorbed to make up insufficient prime mover torque. If the frequency decay is slow enough, the turbine governor response comes into play to reduce the torque error.

3) Load Shedding on Over-Load. A system over-load results in locally high currents, locally depressed voltages and in some cases, system frequency depression. However, with high speed automatic voltage regulation, the voltage depression may be short term or may not occur, depending on the suddenness of the overload condition and remoteness from voltage regulating equipment. Decreasing voltage may cause increased current, and therefore, increased VAR loading by the transmission lines. This can result to low power reserve [2].

$$P_{srj} = \sum G_i \left(p_{ci} - P_i \right) \quad (2)$$

where,

P_{dfni} = Power deficit on sub-network I for the under-frequency limits n,

I = index on sub-networks (internal data),

J = index on generators (internal data),

N = level of under-frequency: first or second,

G_{ji} = 1, if generator j is connected to sub-network i, 0 if otherwise.

P_{dni} = fixed power deficit for generator j for the under-frequency limit n.

The study analyzes load shedding scheme in an industrial estate, compares it with other schemes such as the power distribution control schemes, dynamic stability tests and load flow simulation. To analyze and determine modern and more effective load shedding schemes or strategies such that power systems are not unnecessarily overloaded beyond their generating capacities, a review of available facility was carried out in comparison with load flow simulation tests.

2. Review of Related Literature

The ability of electric network to accept loads under all possible conditions is an indication of the system adequacy, and it relates to the ability of the generation to meet the system demand. Under pre-loading operations, considerations are usually given on typical system constraints such as generation unavailability due to fault or maintenance requirements, variations in system loads, as well as its inability to remain stable or regain stability after a disturbance [2]. Certain key measures are usually considered which may be configured automatically or may require the operator's initiation.

Transmitted reactive and active power: Any synchronous machine like the generator requires reactive power to establish its magnetic field. This magnetic field is either imported from the grid or produced internally by the machine itself.

Turns ratio of the transformer: Another important method for controlling the voltage in power system is by changing the turns-ratio of transformers. Certain transformers are equipped with a number of taps on one of the windings. Voltage control can be obtained by switching between these taps. Switching during operation by means of tap changers is very effective and useful for voltage control. Normally, the taps are placed on the high-voltage winding since lower currents will be switched.

In a four-pole alternator, two cycles are generated in each oil per revolution. Since the number in cycles per revolution equals the number of pairs of poles, the frequency of the generated voltage is:

$$F = np \tag{3}$$

where,

f = frequency of the generated voltage in hertz

n = engine speed in revolutions per second

p = number of pairs of poles

There are at least two reasons against allowing the frequency to deviate too much from its nominal value. A non-nominal frequency in the system results in a lower quality of the delivered electrical energy. If the frequency is too low (lower than 47 Hz - 48 Hz from the nominal value), this can lead to damaging vibrations which can degenerate into complete power system collapse.

Automatic synchronization: In automatic synchronization, the automatic synchronizer (device 25A) monitors the frequency, voltage and phase of the oncoming generator, provides correction signals for voltage and frequency matching and provides the breaker closing output signal. Automatic synchronizers could be either phase-lock type or anticipatory type.

The reactive power equations can be written as:

$$Q_s = \frac{V_S^2 - V_s V_R \cos\delta}{X} - \frac{V_S^2 4}{X_c}$$

$$Q_R = \frac{-V_R^2 + V_s V_R \cos\delta}{X} + \frac{V_R^2 5}{X_c}$$

where,

P_s = Power at the sending end

P_R = Power at the receiving end

Q_s = reactive Power at the sending end

Q_R = reactive Power at the receiving end

δ = Phase angle difference between the two buses

X = Series reactance of the line

X_c = line charging capacitance

From the Equations, the active power transfer is determined by sending and receiving end voltages, series reactance of the line and phase angle difference between the sending and receiving end voltages [3] [4] [5].

The distribution sub-station is usually the delivery point of electric power in large industrial or commercial applications [5].

Expanded-radial distribution system: The advantages of the radial system may be applied to larger loads by using a radial primary distribution system to supply a number of unit substations located near the load centers with radial secondary systems.

3. Methodology

3.1. Materials

The case-study of this work is the Export Free Zone complex located in Calabar, Nigeria. The giant Industrial complex is equipped with three different units of power generating sets. These materials were deployed in these investigations; though for the purpose of reporting this article; the Essential and Emergency power generating sets were configured. In addition, computer software devices and relevant man-machine-language commands and simulations were used to aid the study. This report is an extract from the comprehensive study carried out.

Computer Software

The software used in this stimulation are as follows:

1) Power Tools for Windows, PTW, version 4.5.25 edited by SKM system analysis inc. TMS (transient motor starting) module.

2) I SIM (SKM Power Tools), PTW-32 version 4.5.2.0 (industrial dynamic simulation) module.

3) Power Tools for Windows, PTW, and version 4.5.2.0 edited by SKM system Analysis Inc.

3.2. Research Method

The study was carried out through empirical measurements and simulations. The software used was uploaded to the laptop with the relevant data(s) measured. With the aid of RS-232 communications cable, connection was established between the measurement tool hooked to the generator control panel and the laptop computer. Results obtained were plotted on the computer and each result saved with a particular file name. Part of the results obtained is presented in this report.

3.2.1. Simulation Technique

In this simulation, the third generator was put on line with the aim of later tripping one of the two main generators that were previously running. The three main generators were running in parallel with balanced load sharing. The downstream breakers A and B were supplied by one power transformer while all tie-breakers were closed. Also, all normal operations were on-going.

At $t = 0$ s, the simulation began.

At $t = 1$ s, one of the main generators 11 KV, 23 MW, (IZAN-83397) was tripped.

Loss of the essential generator:

Two main generators were running in parallel with the essential generator. The main generators were operating with balanced load sharing and the essential generator was set at base load. The two downstream breakers A and B were supplied by one power transformer while all tie-breakers were closed. Normal operation was on-going.

At $t = 0$ s, the simulation began.

At $t = 1$ s, the essential generator: 6.6KV, 5.2MW (IZAN-83369) was tripped.

3.2.2. Stimulation Data

The simulation data are shown in Table 1 & Table 2.

Table 1. Generator input data.

s/n	generator name	generator tag.number	rated capacity (kw)	rated voltage (v)	x"d (pu)
1	Turbine generator 1	IZAN-83331	2000	1100	0.2
2	Turbine generator 2	IZAN-83364	2000	1100	0.2
3	Turbine generator 3	IZAN-83297	2000	1100	0.2
4	Essential generator	IZAN-83269	5200	6600	0.1
5	Emergency generator	IZAN-83101	1400	400	0.1

Table 2. Cooling medium pump motor input data.

S/N	Cooling medium pump motor (IWBE-92202)	Motor Data
1	Motor moment of inertia	11.6 kg·m^2
2	Motor nominal torque	3846 N·m
3	Motor nominal current	64 amperes
4	Motor nominal current	6.05 × nominal current
5	Motor nominal speed	1500 rpm
6	Motor nominal factor	0.8
7	Motor voltage rating	6600 volts
8	Motor power rating	598 KW
9	Load moment of inertia	3.8 kg·m^2
10	Load nominal torque	3461 N·m
11	Load nominal speed	1500 rpm

4. Results

The results of the simulation carried out are the curves of the power, voltage, current bus frequency, turbine generator speed, electrical and mechanical torque against time. These are presented from Figures 1-9.

Determination of the effective load shedding for electric power plants was carried out using simulation techniques. Three generators were put on parallel operation with balanced load shedding of 11,500 kW at 0.8 power factor each. After some time one of the generators was suddenly switched off without balancing the load. Under this test module, five different tests and measurements were made. The results obtained are presented as follows: The first test and measurement were on the variation of generator real and mechanical power with time (Figure 1). The second measurement was on the variation of the generator

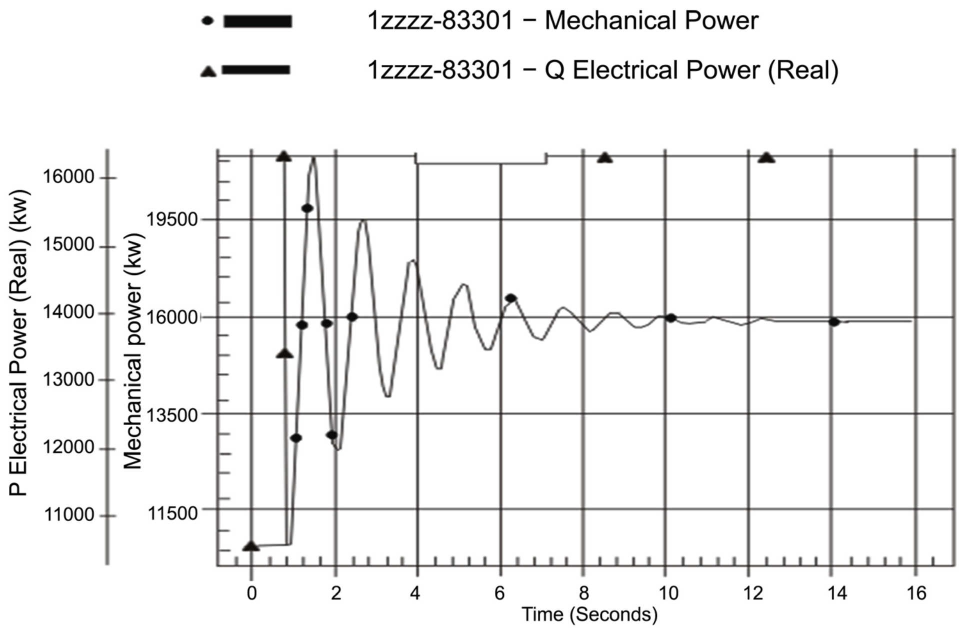

Figure 1. Variation of generators' real and mechanical powers with time.

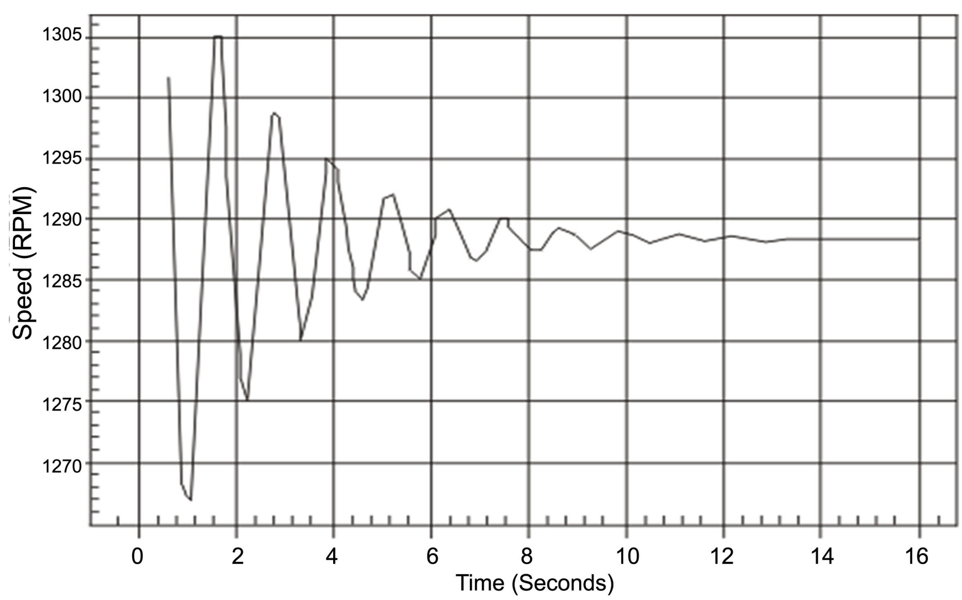

Figure 2. Variation of generator speed with time.

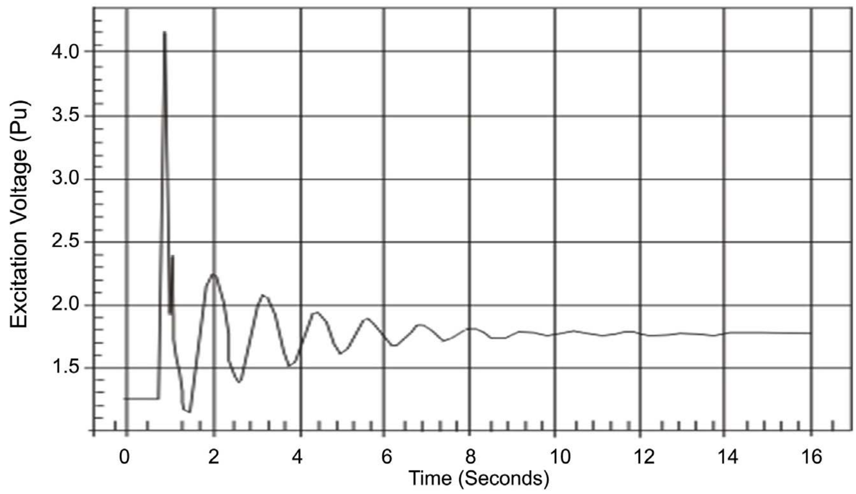

Figure 3. Variation of excitation voltage and time.

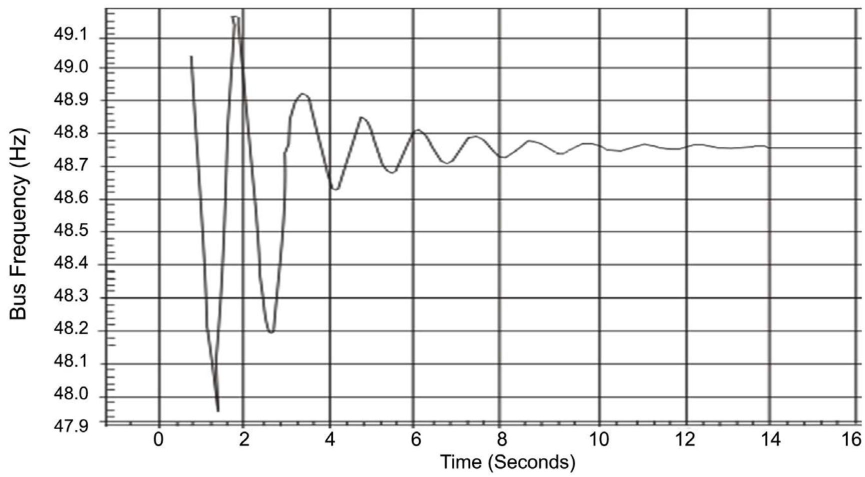

Figure 4. Variation of bus frequency with time.

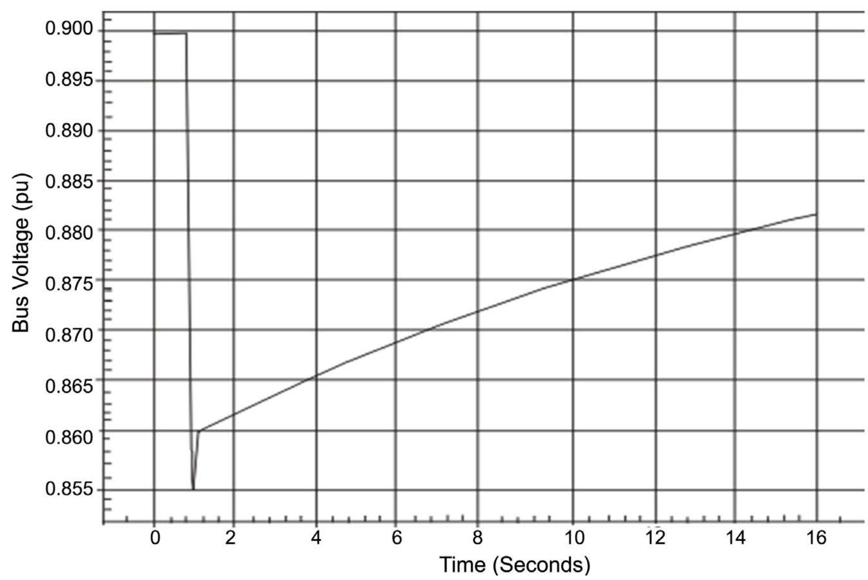

Figure 5. Variation of bus-bar voltage with time.

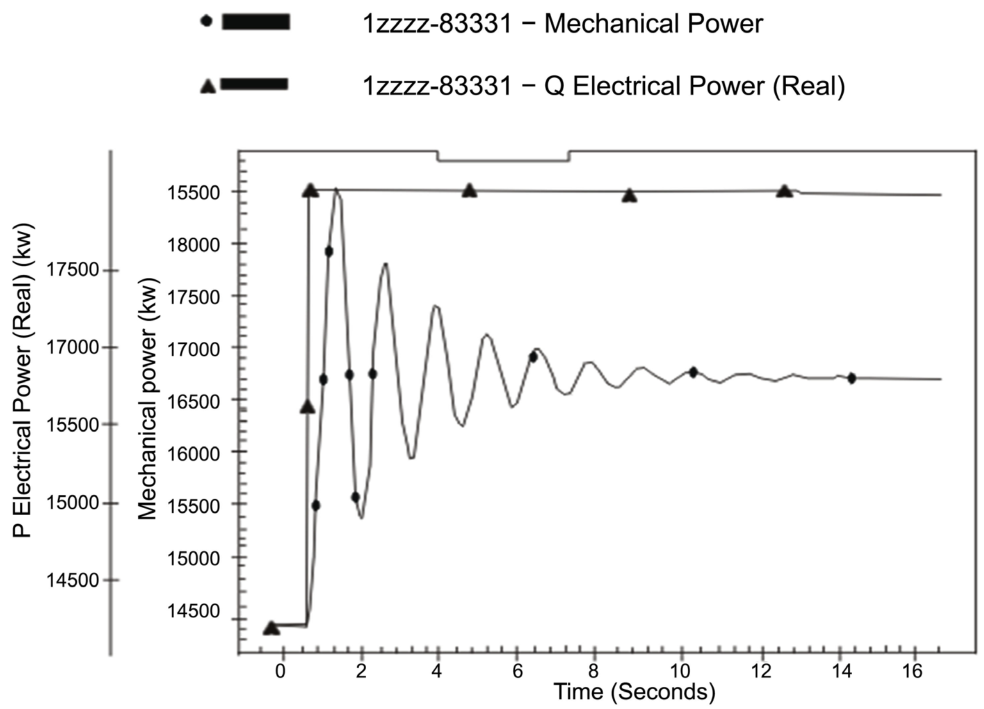

Figure 6. Variation of generator active and turbine mechanical power with time.

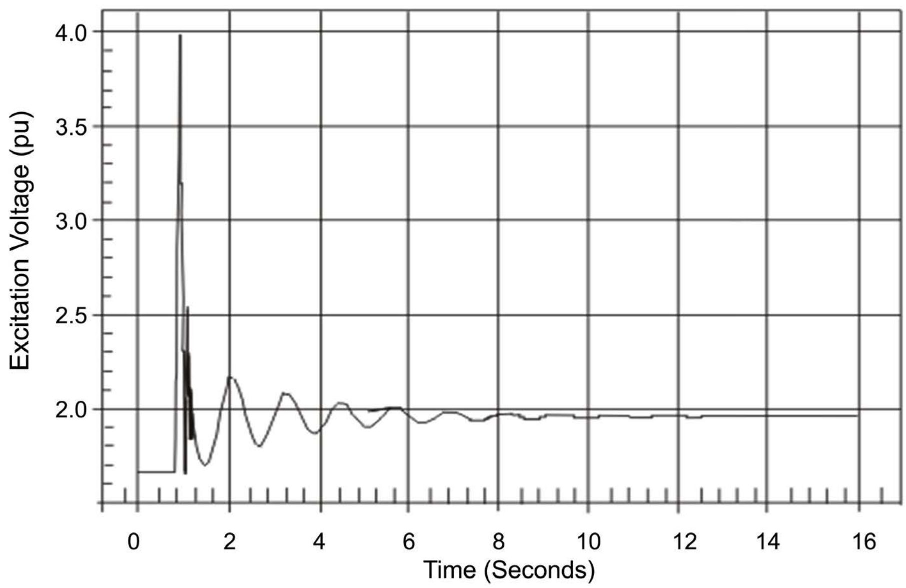

Figure 7. Variation of generator excitation voltage with time.

speed on loss of one of the three generators (**Figure 2**), while, **Figure 3** shows the variation of the generator's excitation voltage as time varied. **Figure 4** and **Figure 5** show the variations in bus frequency with time and the bus-bar voltage with time respectively.

The second tests and measurements took place when the essential generator was running in parallel with two other generators and suddenly the essential generator was tripped off; thereby throwing a portion of the load it was carrying to

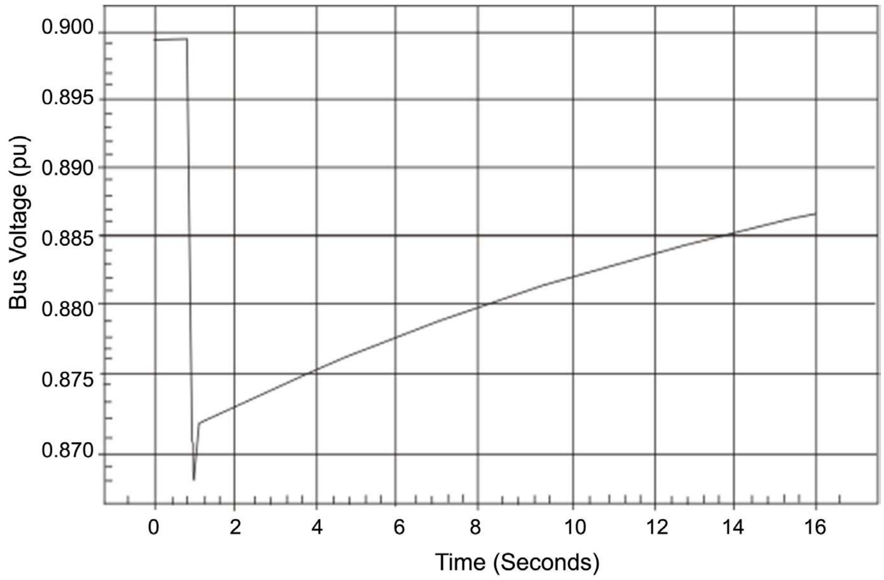

Figure 8. Variation of 11 KV bus voltage with time.

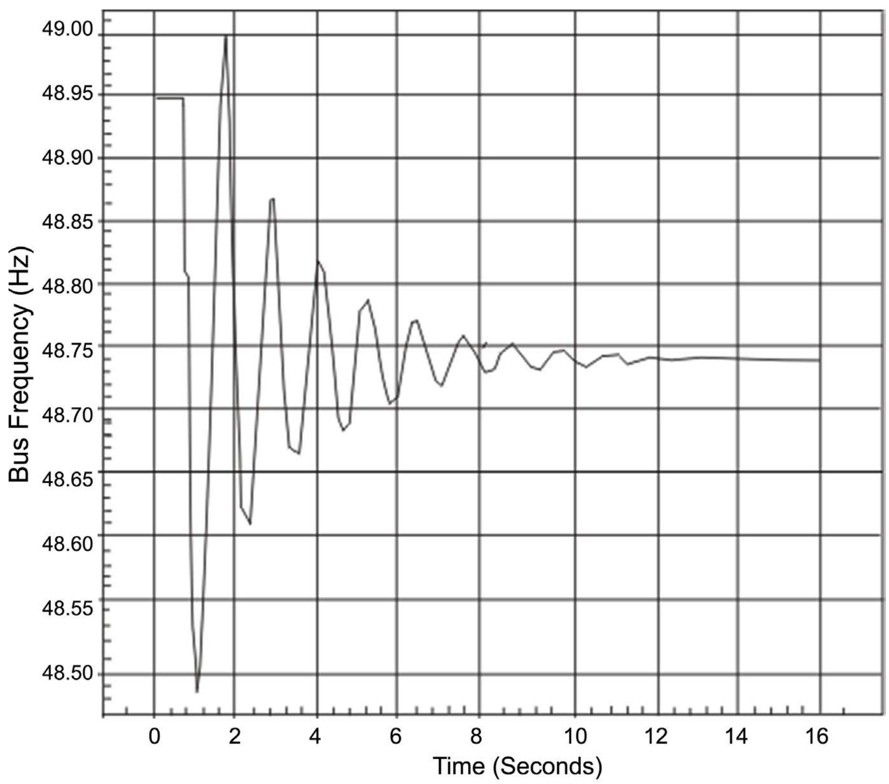

Figure 9. Variation of 11 KV bus frequency with time.

the other two generators. **Figure 6** shows the results obtained on the variation of the generator's active and mechanical power with time. **Figure 7** presents results obtained on the variation of generator's excitation voltage with time. Similarly, **Figure 8** and **Figure 9** present results obtained on variation of the bus voltage and Bus frequency with time respectively.

Discussion of Results

1) Loss of one of three turbine generators

The three generators were running on balanced load sharing of 11,500 kW at 0.8 power factor each. After the trip, the two remaining turbine generators were now loaded to 16.300 kW each, while the mechanical power fluctuated to 16,500 kW (Figure 1). When one of the generators was lost and the loads were thrown on the other two, the mechanical power of the two remaining generators fluctuated for a period of about ten seconds before it stabilized. However, when generators with the same engine parameters and set-points were running in parallel, they shared the system load equally. When any of the generators dropped out or tripped, the remaining generators also shared equally the portion of load previously carried by the tripped generator. This was also noted by [6].

Also, there were noticeable fluctuations in the speed of the remaining two generators. It became stable at about 12 seconds after the loss. The variations were 0.3 per cent of the nominal speed value (Figure 2). The excitation voltage fluctuated from 1.2 (pu) to 4.5 (pu) when the bus voltage dipped as a result of the additional load. It then came down and stabilized at 1.8 (pu) after few swings. This is illustrated in Figure 3. The frequency also swung from 47.9 Hz to about 49.95 Hz and finally stabilized at 48.75 Hz, after about ten seconds (Figure 4).

The bus voltage dipped to about 85.5 per cent of the nominal value because of the sudden load on the generators, and there after increased gradually to about 88 per cent after eighteen minutes (Figure 5). The results are within the specification requirements (maximum percentage voltage drop of 20 per cent at the farthest terminal point). Normally, there is always a drop in the bus frequency and a spike in the excitation voltage when generator takes up additional load because of the drop of 4.5 per cent; which in this case is within specification requirements of 20 per cent maximum at the farthest terminal point as given by [7] [8] [9].

2) loss of the essential generator with two turbine generators running.

When the Essential Generator was tripped, two remaining turbines were each loaded to 17,800 kW from their initial loads of 14,500 kW. The mechanical power of each of the turbines surged at 18,500 KW but later stabilized at about 17,000 kW after ten seconds (Figure 6).

There was a spike in the excitation voltage (Figure 7). This was as a result of the sudden drop in the bus voltage when the turbine generators took over the loads that were initially on the essential generator as seen in Figure 8. It then stabilized at about 2.0 (pu) after about eight seconds. The bus voltage initially dropped from 0.900 (pu) to about 0.870 (pu) and immediately rose to 0.873, before increasing gradually to about 0.887 (pu) within next 18 seconds.

Figure 9 shows how the bus frequency dropped sharply from 50 Hz to 48.45 and shot up to 50.05 Hz within a minute. It then swung back and forth for the next eight minutes before stabilizing at about 48.70 Hz. This means that there was a reduction in the turbine speed as a result of the sudden load. Generally, it took less than 10 seconds for the system to regain its stability after losing the Essential generator. The surge in the mechanical power of the turbine engine before it finally stabilized, the spike in the excitation voltage and the drop in the bus frequency are again as observed in similar tests and measurements carried out by [10] [11] [12].

5. Conclusion

Various load shedding schemes such as conventional load shedding scheme, Programmable Logic Controller (PLC)-based load shedding scheme and intelligent load shedding scheme have been discussed. From the tests and the measurements taken, it was observed that the real and reactive powers from the generator and the mechanical power from the turbine engine were stable when the load shedding controller was switched on, as compared to when it was off. The engine speed, the bus-bar frequency and the output voltage of the generator stabilized within a much shorter time (about 8 seconds) when the controller was switched on than when it was on the off condition. These confirm that the stability of a power system is much enhanced under the load shedding controller which ensures that the power consumed by the loads is kept lower than the generating capacity of the turbines.

Conflicts of Interest

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

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