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Investigation of Power Station Collapse: A Case Study of Steam/Gas Turbine Sapele Power Station, Oghorode, Delta State, Nigeria

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Abstract: This study has investigated sapele power station electric power availability in terms of system collapse. The station with total installed capacity of 1020 MW reliability data for 2003 was collected from the performance department for fault analysis. The station with six, 120 MW steam turbines and four, 75 MW gas turbines in 2003 only ST01 and ST06 were in operation such that the best optimal power the 2 units could inject into the interconnected area network was 171 MW. The fault analysis revealed that due to load demand resulting in system frequency fluctuation, steam turbine operating No. 1 caused system collapses in the interconnected area 17 times, while steam turbine operating No. 6 caused 19 system's collapse. The maximum load demand that was recorded in either of the units that resulted in system collapse was 85 MW, meaning the solution to the problem lies in improvement of generation since the generators have been in use for the past 27 years and now have depreciation value of 56.77%, thus, suggesting complete overhauling or replacement of the units. The research also revealed that the area frequency control error criteria and all other system's control parameters as enumerate in study three were operationally put in place to ensure safe operation of the station for electric power availability, while the statutory limit of frequency of ±4% of the standard value (50 Hz) allowed for steady-state stability of the system could not be maintained due to load demand hence, the synchronous machines pull-out of synchronism resulting in system collapse. The research also shown that the station has parasitic energy of 7.25% far above the standard value of 5%.

Key words: Optimal power, energy, availability, frequency, turbine-generator, interconnected-area, stability, load demands

INTRODUCTION

The reason for the system collapse is attributable to several factors namely: system frequency fluctuation due to disequilibrium between the power generated and load demanded with the load on the higher side of the beam, lines congestion, vandalization in underdeveloped nation, etc. Until all these gap is closed, the uninterrupted and stable electricity power supply, which everybody clamour for would continue to elude us.

In this research, we present the causes of system collapse from power stations the source of electric current. Sapele power station was commissioned with 6 steam turbines having an installed capacity of 120 MW turbine^{-1} and 4 gas turbines with generation capacity of 75 MW each. The supposed power to be injected into the national grid is 1020 MW. At the time of this study, only ST01 and ST06 were in operation. The remaining 4 steam turbines and gas turbines were shut down for different adduce faults. At the best optimal performance the maximum ST01 and ST06 could inject into the interconnected networks was 171 MW in the month of July 2003. This shortfall in the expected power from the station has resulted in massive Load shedding of 33 kV feeders as directed by the area control center. For the federal government of Nigeria to meet up with 1 her 7 points agenda in the present political dispensation of president Umaru Musa Yar'Adua, studies like this becomes of very paramount importance in order to usher in the so much desired sustainable energy development that can boost the nations Gross domestic product and Gross nation product indices.

MATERIALS AND METHODS

In order to successfully investigate the power plant availability and quality supply of electric energy to end-users the data obtained from the performance department and the logbooks were used. Unrecorded opinion of some inhabitants of the interconnected area

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were also sought to ascertain their level of satisfaction of the power utility performance. The methodology adopted in this research includes:

- The system's operation in terms of control mode and effect of frequency fluctuation
- Analyzing the system in order to justify the parametric qualities that causes system collapse
- Faulty analysis of the data's from the performance department and the control room logbooks
- Stability analysis and the factors that affects power system's availability
- Results analysis that enable conclusion of the research

System's operation: The system operating frequencies in the research includes 25, 50 and 60 Hz. Every nation base on the advantages and disadvantage, peculiar to the frequencies decides on which frequency to operate her power supply system. The operating frequency, 50 Hz for generation, transmission and distribution of electric power in Nigeria is chosen over 60 Hz because the systems transmission lines, generators and transformer have smaller reactance's and does not result in incandescent lights flickering. Power Holding Company of Nigeria, PLC (PHCN) the sole operator of electric power in Nigeria operates an interconnected system and the central control center, Oshogbo monitors information including area frequency, generating units' outputs and tie-line power flows to interconnected areas. Information like, frequency is used by automatic Load-Frequency Controller (LFC) in order to maintain area frequency at its scheduled value ±4% of 50 Hz (PHCN, 2006) and the net tie-line power flow out of this area at its scheduled value (PHCN, 2002).

During operation raised and lower reference power signals are dispatched to the turbine-governors of controlled units with incorporated power frequency converter. In the case of Nigeria most times, this control criterion cannot be achieved because of its very low availability of the generating units which then influence the area daily load curve and depicts total load demand of the different load area. Figure 1 shows a simplified block diagram of turbine-governor control (Glover and Sarma, 2001).

System control mode: The closed loop control system employs power to frequency converters such that the transfer functions is equal to:

$$=\frac{G_T}{1+G_T H_1} \tag{1}$$

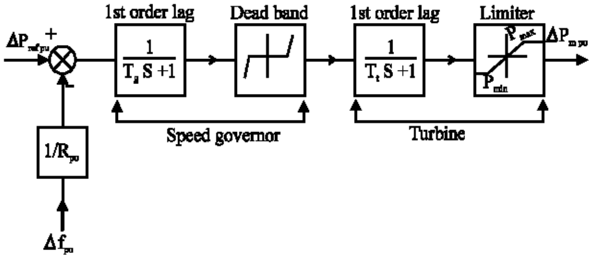

Fig. 1: Block diagram of a non reheat steam/gas turbine governor

Where, $G_T = G_1 \times G_2 \times G_3 \times G_4 \times G_5$ is the open loop transfer function and equation becomes:

$$G(s)=K_c S\times\frac{1}{T_g S+1}\times\frac{K_1}{(S+1)^2}\times\frac{1}{T_t S+1}\times\frac{K_2}{S^3} \tag{2}$$

$$=\frac{K_1 K_2 K_c S}{S^3(S+1)^2(T_g S+1)(T_t S+1)} \tag{3}$$

Therefore,

$$\frac{P_{max}}{P_{ref}}=\frac{f_m}{f_{ref}}=\frac{G(s)}{1+G(s)H_1}$$
$$=\frac{K_1 K_2 K_c S}{S^3(S+1)^2(T_g S+1)(T_t S+1)} \tag{4}$$

$$1+\frac{K_1 K_2 K_c S}{S^3(S+1)^2(T_g S+1)(T_t S+1)}K_f S \tag{5}$$

$$=\frac{K_1 K_2 K_c S}{S^6(S+\frac{T_g+T_t+K_1 K_2 K_f K_c}{T_g T_t})+1} \tag{6}$$

Let,

$K_1\,K_2\,K_C\,S = TK_c\,S$, integral gain

While,

$K_1 K_2 = T$, proportiate gain

$K_C S$, $K_f S$ = power to frequency converters

and

$$\frac{T_g+T_t+K_1 K_2 K_f K_c}{T_g.T_t}=T_D \text{ differentiae gain}$$

Thus,

$$G(s)=\frac{TK_c S}{S^6(S+T_D)+1} \tag{7}$$

Splitting Eq. 7, into its partial form, we have:

$$G(s)=\frac{A}{S^6}+\frac{B}{S+T_D}+\frac{TK_c S}{1} \tag{8}$$

Equation 8 shows that the control mode is a PID controller, as noted for complex systems, it becomes increasingly difficult, if not impossible to distinguish the individual modes of control (Raven, 1978). However, regardless of the various modes that may be present, it becomes relatively simple matter to determine whether K_c is finite or infinite. For an infinite value, the integral action predominates and there is no steady state error due to variation in the external disturbance. For a finite value the system behave as a proportional control system. As the system is responding perfectly to deviation in power demands, all three types of control modes are involved.

Consequences of changes in supply frequency: The standard allowable frequencies acceptable in Nigeria power system (Onohaebi and Igbinovia, 2007; PHCN, 2006) and resulting consequences are:

- ±4% of 50 Hz for generating stations
- ±5-15% voltage policy for 330 kV transmission lines
- ±10-15% voltage policy for 132 kV transmission lines
- ±10% in the operating frequency results in motor speed reduction
- ±20% in the operating frequency results in machine tools and other motor driven speed with 20% increase affects torque speed, power factor efficiency, while temperature rise remains satisfactorily in most cases

System quality parameters effect

Generator terminal Voltage, Load and Frequency Control (VLFC): The operation of synchronous machines coupled to prime moves as unit known as a generator, applying Faraday's law of electromagnetic induction produces electromotive force that drives the output voltage given as (Hughes, 1959; Desphande, 1994; Symond, 1980):

$$E_{rms} = 4.44f\,\phi_{max}\,T \text{ (volts)} \qquad (9)$$

$$= 4.44\,(K_d)\,(K_c)f\,B_{max}\,A\,T\sin\theta \text{ (volts)} \qquad (10)$$

Where,

T = Turns in series in the coil/phase

A = Area of each turn (m^2)

n = Speed of rotation in revolutions/second

f = No. of revolutions/second (Hz)

ϕ_{max} = Maximum sinusoidally distributed flux in the airgap of the machine/pole (Webers)

B_{max} = Maximum flux density (Telsa)

K_d, K_c = Winding distribution factors

This terminal voltage can be controlled in line with the load demand. In practice high-gain, fast-responding exciters provide large rapid increases in field-voltage E_{fd} during short circuits at the generator terminals in order to improve transient-stability after fault clearing. This generator frequency is usually an appropriate control signal for governing the mechanical output power of the turbine. Load fluctuation brings about system voltage dips thus, the steady-state frequency-power relation for turbine-governor control is Glover and Sarma (1994):

$$\Delta P_m = \Delta P_{ref} - 1_{\Delta F}/R \qquad (11)$$

While the area frequency control is given by:

$$ACE = (P_{tie} - P_{tie\ sched}) + B_f\,(f - 50) \qquad (12)$$

The change in reference power setting ΔP_{ref} of each turbine governor operating under LFC is:

$$\Delta P_{ref} = -k_i \int (ACE)_{dt} \qquad (13)$$

Where,

ΔF = Change in frequency or steady-state frequency error

ΔP_m = Change in turbine mechanical power output

ΔP_{ref} = Change in reference power setting, which is zero during normal operation

R = The regulation constant

B_f = Frequency bias constant for interconnected area

k_i = Integrator gain

As it can be shown or rather depicted in Table 1, practically, the minus sign in Eq. 13 indicates that if either the net tie-line power flow out of the area or the area frequency is low (i.e., if ACE is negative, then the area should increase its generation) and vice versa. The choice of B_f and K_i affects the transient response to the load changes of the interconnected system (Glover and Sarma 1994).

Objectives of Load Frequency Control (OLFC):

- Following a load change, each area should assists in returning the steady-state frequency error to zero
- Each area should maintain the net tie-line power flow out of the area at its scheduled value in order for the area to absorb its own load changes
- In steady-state operation both LFC objectives are satisfied when; ACE is zero in every area and both ΔP_{tie} and Δf are zero

Energy torque relationship: Newton's second law governs the operation of the turbine-generators units operating in a power system, such that Glover and Sarma (1994) and Ogata (1999):

$$J\alpha_m\,(t) = T_m\,(t) - T_e\,(t) = T_a\,(t) \qquad (14)$$

Table 1: System frequency disturbance of sapele power station (Eriamiatoe, 2007; PHCN, 2005)

2003	No. of tripping	Frequency of tripping (Hz)	Load dropped (MW)	Nature of fault	Remark
ST01					
3/01/0713 h	1	Frequency surge	75	No. power outlet	System collapse
4/01/1559 h	1	Frequency surge	71	Excitation fault due to rotor earth fault and rotor over load alarms	System collapse
11/02/1210 h	1	Frequency fluctuation	75	Lack of power outlet	System collapse
2/03/1658 h	1	49.01	80	√	System collapse
6/03/1906 h	-	-	-	-	-
18/03/2154 h	-	-	-	-	-
7/04/1710 h	1	46	76	Lack of power outlet	System collapse
4/04/0359 h	1	Frequency surge	76	Boiler drum level very low	System collapse
8/05/1200 h	1	47.96	84	Lack of power outlet	System collapse
4/061017 h	1	System frequency instability	83	Lack of power outlet	System collapse
30/06/1140 h	1	Under frequency	82	Lack of power outlet	System collapse
01/072251 h	1	49.65	82	System disturbance	System collapse
2/07/0216 h	1	Frequency surges	Not on load	-	
and 1019 h		-			
3/07/0408 h	1	51.10	84	Lack of power outlet	System collapse
8/07/0544 h	1	Under frequency	85	Lack of power outlet	System collapse
12/07/2205 h	1	47.00	82	Lack of power outlet	System collapse
19/07/0949 h	1	Frequency dropped sharply		Lack of power outlet	System collapse
31/07/1107 h	-	-	-	-	-
24/11/0332 h		Sudden frequency surge	-	-	-
29/11/1238 h	1	Frequency rose to 54.00 and dropped sharply to 36.00	70	Lack of power outlet	System collapse
5/12/0455 h	1	Under frequency	74	Lack of power outlet	System collapse
Total	17				
ST06					
3/01/0713 h	1	Under frequency	60	No. power outlet	System collapse
4/01/1559 h	-	-	-	-	-
11/02/1210 h	1	Frequency fluctuation	56	Lack of power outlet	System collapse
2/03/1658 h	1	49.01	57	Lack of power outlet	System collapse, no breaker opened
6/03/1906 h	1	40.10	54	Lack of power outlet	System collapse
18/03/2154 h	1	Under frequency	80	Lack of power outlet	System collapse
7/04/1710 h	1	46	50	Lack of power outlet	System collapse
4/04/0359 h	-	-	-	-	-
8/05/1200 h	1	47.96	50	Lack of power outlet	
4/061017 h	1	Frequency fluctuation	83	Lack of power outlet	System collapse
30/06/1140 h	1	Under frequency	84	Lack of power outlet	Systemcollapse
01/072251 h	1	47.29	85	System disturbance	Systemcollapse
2/07/0216 h and 1019 h	1	Frequency surges	Not on load	-	
3/07/0408 h	1	51.10	83	Lack of power outlet	System collapse, no breaker opened
8/07/0544 h	1	Under frequency	86	Lack of power outlet	System collapse
12/07/2205 h	1	47.00	85	Lack of power outlet	System collapse
19/07/0949 h	1	Frequency dropped sharply		Lack of power outlet	System collapse
31/07/1107 h	1	Frequency fluctuation	84	Lack of power outlet	System collapse
24/11/0332 h	1	Sudden frequency surge	84	Lack of power outlet	System collapse
29/11/1238 h	1	Rose to 54.00 and dropped to 36.00	70	Lack of power outlet	System collapse
5/12/0455 h	1	Under frequency	82	Lack of power outlet	System collapse
Total	19				

ST01-6: Steam turbine No. 1-6, respectively

$$P_m = \omega_m (T_m (t) - T_e (t)) = \omega_m T_a (t) \qquad (15)$$

During operation of the functional units in the station these conditions holds;

$T_e > T_m$ = Rotor speed or electrical frequency is decreasing (neglecting generator losses)

$T_e < T_m$ = Rotor speed or electrical frequency is increasing

Where,

J = Total moment of inertia of the rotating mass (rotor) that stores kinetics energy (kg^2)

α_m = The rotor angular acceleration (rad sec^{-2})

T_a = Net accelerating torque (N-m)

T_m = Mechanical torque (N-m)

T_e = Electrical torque (N-m)

P_{max} = Maximum generator-shaft output power (watts)

ω_m = Rotor angular frequency (radian sec^{-1})

Table 2: Sapele power station energy profile for the 2003 (Eriamiatoe, 2007; PHCN, 2005)

Months	Energy generated (MWh) Target	 Actual	Shortfall from target energy expected (%)	Performance (%)	Energy consumed at station (MWh)	Energy sent out to grid (MWh)	Energy injected into the grid (%)
January	107880	79001	26.78	73.22	5534	73467	93.00
February	97440	73083	25.00	75.00	5203	67880	92.88
March	107880	60423	43.99	56.01	5609	54814	90.72
April	104400	87561	16.13	83.87	6522	81039	92.55
May	107880	62660	41.92	58.08	4450	58150	92.80
June	122400	86143	29.62	70.38	5666	80477	93.42
July	110112	91261	17.12	82.88	5936	85325	93.50
August	84072	76479	9.03	90.97	4949	71530	93.53
September	94320	83486	11.49	88.51	6044	77442	92.76
October	130300	69616	46.57	53.43	5848	63768	91.60
November	126000	53944	57.19	42.81	3550	50394	93.42
December	130200	81043	37.76	62.24	5853	75190	92.78
Total/average (%)	13222884	904640	31.62	68.38	65164	839476	92.75

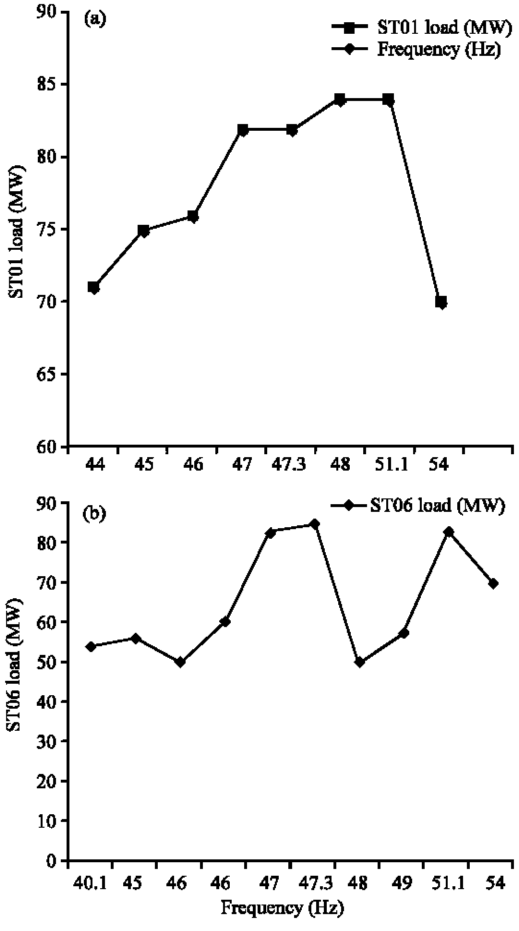

Fig. 2 (a-b): Steam-turbines operating load against the system operating frequency

From Eq. 15 and as experienced in Table 1 generator frequency using appropriate frequency converter is an appropriate control signal for governing the mechanical output power of the turbine.

System operational data: Table 1 shows the station operation frequency fluctuation that occurred in the year,

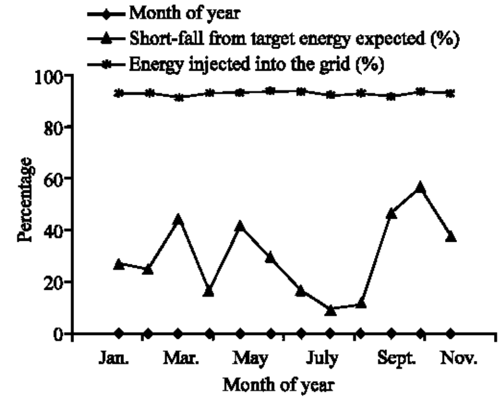

Fig. 3: Station percentage energy profile for the year

while Table 2 presents the station energy profile for the period under consideration. The relationship between the frequency's of interruption and the load demands for the year under review is as shown in Fig. 2a and b, while the percentage shortfall from the target energy and percentage energy injected into the national grid for the period under review is presented in Fig. 3.

Steady state operation stability limit: The real and reactive power transfer on a Transmission Line (TL) in an integrated network is governed by certain factors like:

- Line impedance
- Voltage magnitude
- Angel difference at the line ends
- The role the line is playing in maintaining network stability under dynamic contingencies

For steady state stability limit of an interconnected area the complex power S_R and the real power P_R delivered respectively to the receiving end when the transmission line is loss less are:

$$S_R = \frac{jV_RV_S\cos\delta + V_RV_S\sin\delta - jV_R^2}{X'} + j\frac{\omega_d}{2}V_R^2(\text{kVa}_r) \qquad (16)$$

$$P = P_R = R_c(S_R) = \frac{-V_R V_S}{X'} \sin\delta \text{ (watts)} \quad (17)$$

$$P_{max} = \frac{-V_R V_S}{X'} \text{ (watts)} \quad (18)$$

Where,

V_R and V_S = Positive-sequence line-to-neutral voltages
L and C = Transmission-line constants
X' = The line series reactance per unit length
δ = Phase angel across transmission line
ω = The angular frequency

Transient state stability such as lose of generation, line switching operations, faults and sudden load changes and dynamic stability that involves major disturbances that last longer time period, typically several minutes also contributes to power system non-availability.

RESULTS AND DISCUSSION

Analyzing the performance of the power plant for the period under review Table 1 revealed that though the turbine-generator output were not exceed in the cases of system collapse, but for the fact the area control center has set both the frequency operating limit of the generator and the sub transmission lines, the recorded values at time of system collapses shows short falls below the statutory requirement for the generators and transmission network to remain in both steady-state and dynamic state. Otherwise, consequences highlighted in study will manifest causing dissatisfaction and system operators paying penalties to customers, plus huge lost of revenue due to uncontrollable mean time to restoration on the part of management. Figure 2 clearly shows non-linearity of the frequency of operation against the area load demand, this means that for the disequilibrium in the power plant side of the beam and the consumer side to be carter for there has to be very serious improvement in the amount and quality of energy generated and re-enforcement of the transmission and distribution networks. The energy profile in Table 2 presents the total average percentage short fall from target energy expected to be 31.62%, while of the total energy generated the percentage energy injected into the national grid is 92.75%. The percentage energy profile as depicted in Fig. 3 shows the availability and optimal performance of the station for period under review.

The 36 times, the station experienced system collapse from ST01 and ST06 pulling out of synchronism depicts the fact that in an interconnected system for an error in any of the measuring parameters in any of the connected area to distort and disturbs the entire interconnected system the control center limit the problem to the particular area where the disturbances occurred. In case of sapele power station were only 2 units where in operation the capability to share the demanded load amongst the station units in order to return normal operation was not obtainable hence the frequent system collapses.

CONCLUSION

To buttress the importance of this investigation the national grid was operated outside the frequency control policy 50 Hz ±0.4%, i.e., 49.8-50.20 Hz in 2005 due to inadequate generation availability leading to frequency excursions below the operational limits, thus, an AUFLDR (Automatic under Frequency Load Disconnection Relays) on some 132 kV feeders all over the grid (PHCN, 2006). The fault analysis revealed that due to load demand resulting in system frequency fluctuation, steam turbine operating No. 1 caused system collapses in the interconnected area 17 times, while steam turbine operating No. 6 caused 19 system's collapse. The maximum load demand that was recorded in either of the units that resulted in system collapse was 85 MW, meaning the solution to the problem lies in improvement of generation since the generators have been in use for the past 27 years and now have depreciation value of 56.77%, thus, suggesting complete overhauling or replacement of the units. The research also revealed that the statutory limit of frequency of ±4% of the standard value (50 Hz) allowed for steady-state stability of the system could not be maintained due to load demand hence the synchronous machines pull-out of synchronism resulting in system collapse.

In sapele power plant since only 2 units where in operation the capability to share the demanded load amongst the station units in order to return normal operation was not obtainable hence the frequent system collapses.

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