

Research Article

Stability Studies of the Nigerian 330 KV Integrated Power System

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Abstract

The Nigeria 330 KV integrated power network consisting of seventeen (17) generating stations, sixty four (64) transmission lines and fifty two (52) buses is studied, to investigate the time limits of stability before, during and after occurrence of a three phase (3-0) fault on the largest generating station (Egbin) and to determine also the most affected generating stations and buses in the network. Theswing and torgue equations expressed in time domain was used for the study and the network was modeled in ETAP transient analyzer environment. Transient stability time limit of the system was set to operate at maximum value of ten (10) seconds. Before the fault (between 0.000secs-0.0006secs), the system dynamics was not affected and the peak values of terminal current, rotor angle, frequency, mechanical and electrical power obtained were observed to be within stability region. However, as the fault occurred between 0.0006 secs-0.042 secs, the system dynamics changes, thus affecting the quadrature axis. This change in quadrature axis affected the individual generator's exciter current, exciter voltage, electrical power, mechanical power, frequency, rotor angle and terminal current, though still remain within stability boundary. However, when the fault is cleared within this time, the system returns to its stability region. When the fault lasted beyond 0.042 secs, there is loss of system synchronism. Generating stations that were majorly affected are Omotosho, Sapele, AES and Delta stations. It was observed that the bus voltages connected to these stations deviated from the statutory limit of 313.45 KV-346.5 KV. Their bus voltage values were: Omotosho (361.42KV), Sapele (358.42 KV), AES (350.43 KV) and Delta (364.32 KV). The other buses connected to the other generating stations were however not affected.

The province's population is expected to grow by about 28 percent – or about 3.7 million people – by 2030 and become increasingly urbanized. The structure of the economy will also change as the high-tech and service sectors grow and demand from large industries is expected to grow moderately.

Keywords: PHCN; NIPP; IPP; ETAP; EGBIN; FCT; 3-θ FAULT

Introduction

Transient stability is concerned with the effect of large disturbances due to fault(s) that occur in power system. The most severe is the three phase fault. One way of improving transient stability in power systems is by increasing bus voltage above its nominal value [1], thus making the machine to decelerate fast. This maintains the transmission voltage at the most optimal point or mid-point after a fault is cleared. Transient stability studies involves the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance, and this depends on the location and kind of fault in the network. This may be sudden application of load, loss of generation, loss of large load or a fault on the system [2]. Transient stability studies determines the machine power angles, speed deviations, electrical frequency, power flow of machines, lines, transformers and the bus voltage levels [1]. The swing equation is used for transient stability studies (rotor angle stability) and it is seriously affected by the type and location of fault. The nature of the fault means whether it is a three phase or a single phase short circuit fault and the location means whether the fault is on the largest machine in the network or on any other machine(s). Three-phase short circuit fault at the generator bus is the most severe type, as it causes maximum acceleration of the connected machine [3].

Literature Review

The swing equation is the basic equation used to investigate power system transient stability studies.Various numerical methods based on the relevant mathematical modeling of the network and differential evaluation of the machines are applied to solve this equation. It issolved using various numerical methods expressed mainly in time domain. These include: Euler method, Modified Euler method, Runge-

Kutta method using implicit integration, equal area criterion, point by point method and Transient Energy Function (TEF) method [4]. Runge-Kutta method is used to determine the first swing stability limit of power system through checking the existence of peaks of rotor angles of severely disturbed generators in the post-fault period [5]. This method is very fast and accurate in determining the critical clearing time. Transient energy function technique is a valuable tool for use in power systems transient analysis needed for both planning and operating functions [6]. The equal-area criterion predicts power system stability and determines critical clearing angle, however it is only applicable to either a one or two machine system connected to an infinite bus bar [7]. Lyapunov's stability criteria, though applicable to stability studies, but as the network gets more complex and large, it becomes inaccurate [2]. The three-phase short circuit at the generator bus is the most severe type [3]. Considering Nigeria power system consisting of seventeen generating stations, fifty two (52) buses and sixty four (64) transmission lines, is gradually becoming large and more complex, effective analysis of such system could only be carried out effectively, efficiently and accurately by the aid of digital computers and the required software. Matlab/Simulink and Etap Transient analyzerare some of such Soft wares/Programs used to study transient

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stability. Matlab/Simulink is used to consider stable, critically stable and unstable state of a multi-machine power system and obtained the individual generator angles [8].

Various control methods and controllers have been developed over time to ensure that, after a very sudden and large disturbance, the system still maintains stability by adjusting its protective schemes and control actions [9]. The transient stability control scheme is very difficult to implement because a disturbance that causes instability can only be controlled if a significant amount of computation (analysis) and communication is accomplished [10]. Time domain simulation method using the swing equation was used by [8] to assess the transient stability by setting the fault clearing time (FCT) randomly to determine whether the system is stable or unstable after a fault is cleared.

Equations relevant to the study

The swing equation, torque equation, equal area criteria, and the determination of the time response equivalent to the rotor angle of the machines.

Swing equation (Rotor angle determination)

This is the fundamental equation that determines rotor dynamics in transient stability studies and it is a non linear differential equation that is solved accurately using digital computer program. The equation is given below:

$$M\frac{d^2\delta}{dt^2} + D\left[\frac{d\delta}{dt}\right] = P_m - P_e = P_a \tag{1}$$

Where:

M = angular momentum (joules-sec/rad)

D = damping coefficient

 $P_m = mechanical power; p_m = p_{mo} - \Delta p_{mo}$

 P_{mo} = input mechanical power

 Δp_{mo} = change in input mechanical power due to governor action

P_e = output mechanical power as modified by voltage regulator

 $P_a = net accelerating power$

$$\Gamma = time$$

P_= electrical power

Torque equation

 $T = \frac{\pi p^2}{8} \phi_{air} f_r \sin \delta$

Where:

T = mechanical torque

P = number of poles

 $\varphi air = air-gap flux$

 $f_r = \text{rotor field MMF}$

 $\boldsymbol{\delta}$ = power (rotor) angle

This equation gives the relationship between mechanical torque,

stator voltage, rotor angle, excitation current and voltage of the generator.

Page 2 of 11

Changes in any of these quantities in the two (2) equations causes the rotor speed and acceleration to fall into the three conditions as shown in the below Table 1.

Equal area criteria

Thiscriteria means all energy gained from the turbine during acceleration period must be returned back to the system by the rotor. It is also used to determine the critical clearing angle. This is given in the equation below

$$E_1 = \int_{\delta_0}^{\delta_{e_1}} (P_m - P_e) d\delta = A_1$$
(3)

$$E_2 = \int_{\delta}^{\delta_m} (P_e - P_m) d\delta = A_2 \tag{4}$$

$$\left.\frac{d\delta}{dt}\right]^2 = \frac{2}{M} \int_{\delta_0}^{\delta} d\delta \tag{5}$$

The critical clearing time is given as

$$t_{cr} = \sqrt{(\delta_{cr} - \delta_0) \cdot \frac{4H}{\omega_0 P_m}} \tag{6}$$

Basic numerical equation used to determine time response equivalent to rotor angle

It gives the corresponding time of the rotor angular displacement. It is obtained based on the mathematical concept and it makes use of numerical integration packages based on mathematical concepts. The equation for the basis of the numerical method used is given below

$$\Delta \delta_n = \Delta \delta_{n-1} + \frac{\Delta P_{n-1} + k_4}{M} (\Delta t)^2 \tag{7}$$

Where δ_n and $\Delta \delta_{n-1}$ are rotor angle changes. Δt is a very small time interval (usually 0.05 sec). It gives a detailed numerical solution of the swing equation and requires little iteration. Hence, it is simple, easy to understand and gives minimal round off errors.

Etap (Transient analyzer)

(2)

ETAP is a dynamic stability program that incorporates comprehensive dynamic models of prime movers and other dynamic systems. It has an interactive environment for modeling, analyzing, and simulating a wide variety of dynamic systems. It provides the highest performance for demanding applications, such as large network analysis which requires intensive computation, online monitoring and control applications. It is particularly useful for studying the effects of nonlinearity on the behavior of the system, and as such, it is an ideal research tool [9].

Performing power system transient stability is a very comprehensive task, that requires the knowledge of machine dynamic models, machine control unit models (such as excitation system and

Condition		Net Power (pa)	Rotor Speed	Rotor acceleration	
1	P _e =p _m	Zero	Constant	Zero	
2	P_>p	Positive	Increasing	Positive	
3	P_ <p_< td=""><td>negative</td><td>Decreasing</td><td>Negative</td></p_<>	negative	Decreasing	Negative	

 Table 1: Description of rotor speed and acceleration under certain conditions.

automatic voltage regulators, governor and turbine/engine systems and power system stabilizers) numerical computations and power system electromechanical equilibrium phenomenon.

Aim

To investigate transient stability limits of the generators in the Nigeria 330 Kv integrated power project (NIPP) before, during and after system disturbances due to fault of the generating station(s) in the network in time domain. Etap 4.0 (power station transient stability analyzer) is used to model and solve the network and machine differential equation interactively.

Methodology

The stability limits of Nigeria 330 KV power network consist of Seventeen (17) Generating Stations, Fifty Two (52) buses and Sixty Four (64) Transmission lines is studied to investigate the limits of stability before, during and after disturbance. A one line diagram as well as the transmission line parameters and generator installed and available capacities of the network are shown in appendix A, B and C respectively. In this study, three phase $(3-\theta)$ short circuit fault on the largest generator (EGBIN with available output capacity of 1320 MW) is considered and analyzed graphically. The impact it will have on other generators rotor angles, exciter currents, exciter voltages, electrical power, mechanical power, frequencies, terminal currents and the entire stability of the network are also determined. Theswing equationexpressed in time domain is solved using the Runge-kutta (using the predictor-corrector routines) and equal area criteria approach in ETAP environmentis used for the analysis. In cases of fault(s), it randomly set up a fault clearing time (FCT) for the machines in the network and solves all the complex differential equations of all equipment in the network.

Modeling the Nigeria 330 KV Integrated Power Network Using Etap

The Integrated Nigerian 330 KV Integrated Power Project (NIPP) interconnects all the generating stations and load centers. The system consists of synchronous generators, motors, transmission lines, transformers, loads and protective devices. Figure 1 below shows the model of the network used for this study. This is obtained by modeling the parameters (bus voltages, transmission line parameters transformers ratings and their loadings, generators ratings and their power limits) as obtained from Power Holding Company of Nigeria (PHCN), while Figure 2 shows the transient stability simulation results obtained.

The simulation time is set from 0 sec-10.0 secs while subjecting EGBIN to a three-phase short circuit fault, and the behavior of the network is obtained graphically as shown in Figures 2-13 below.

Results and Discussions

The Nigeria 330KV integrated power network consisting of seventeen (17) generating stations, sixty four (64) transmission lines and fifty two (52) buses is studied, to investigate the limits of stability before, during and after three phase $(3-\theta)$ fault on Egbin power station. When $3-\theta$ short circuit fault occurred at Egbin generator, the system dynamics changes, thus affecting the quadrature axis. This change in the quadrature axis affects the generator's exciter current, exciter voltage, electrical power, mechanical power, frequency, rotor angle and terminal current. Tables 2a, 2b and 2c shows the results obtained and gives the stability limits of these electrical quantities before, during and after a three phase $(3-\theta)$ fault. Figures 2-13 shows a plot of how this fault affects the behavior of the other generators in the network. It was observed that before the 3- θ pre-fault, the peak values obtained between time range of 0.000 Secs-0.0600 Secs operates within the



J Electr Electron Syst

Page 4 of 11





J Electr Electron Syst ISSN: 2332-0796 JEES an open access journal

Page 5 of 11





Page 6 of 11





Page 7 of 11





J Electr Electron Syst ISSN: 2332-0796 JEES an open access journal

Page 8 of 11





Page 9 of 11





Page 10 of 11

Generators	Mechanical Power (MW)	Electrical Power	Terminal Current(A)	Rotor angle	Frequency (Hz)	Exciter Current	Exciter Voltage
AES	203.27	203.34	10,200	21	49.55	1.55	3.83
Afam I-V	46.41	46.24	3,080.23	32	50.01	1.49	1.70
Afam VI	371.86	371.72	25,992.49	19	50.00	1.52	3.68
Egbin	788.42	788.50	53,732.21	23	49.90	1.92	5.12
Geregu	62.22	62.16	4,441.23	28	49.98	1.05	3.20
Jebba	585.72	585.92	37,873.82	32	49.96	0.70	5.02
Kainji	214.46	214.60	14,678.85	43	50.00	2.10	3.92
Okpai	150.53	150.03	9,031.28	38	50.00	1.48	3.68
Olorunshogo phase 1	50.28	50.32	3,285.72	32	49.99	1.50	2.57
Olorunshogo phase 2	106.99	107.01	6,505.20	16	49.87	1.41	3.63
Sapele	161.94	161.97	10,540.02	41	49.86	0.40	3.72
Shiroro	377.53	377.06	24,320.26	38	50.00	1.80	4.38
Trans-Amadi	77.78	78.00	4,763.4	26	49.76	1.57	3.62
Omotosho	45.27	45.37	2,986.23	29	49.65	1.60	0.98
Ibom	66.45	66.24	4,273.58	23	50.00	1.30	3.45
Omoku	68.46	68.48	4,449.87	20	50.00	1.80	3.57
Delta	381.01	381.03	24,900.48	24	49.54	2.05	4.70

Table 2a: 3-Phase Pre-Fault Peak Values at 0.000 to 0.060 Sec, During Fault Peak Values at 0.061 Secs -0.4220 Secs.

Generators	Mechanical Power (MW)	Electrical Power (MW)	Terminal Current(A)	Rotor angle (Degree)	Frequency (Hz)	Exciter Current (p.u)	Exciter Voltage (p.u)
AES	239.7	543.56	37,292.02	72	51.15	2.27	1.62
Afam I-V	54.65	92.60	10,675.59	75	50.48	0.99	0.73
Afam VI	440.21	741.27	89,414.17	64	50.60	2.56	1.84
Egbin	938.23	1796.65	186,838.01	88	51.40	2.98	2.16
Geregu	74.04	125.95	15,277.83	72	50.10	1.86	1.34
Jebba	697.01	1166.75	130,285.94	82	49.48	2.92	2.11
Kainji	255.21	426.25	50,495.24	81	50.63	2.32	1.62
Okpai	178.81	302.18	31,067.60	81	49.20	2.17	1.58
Olorunshogo phase 1	59.72	101.14	11,302.88	77	50.32	1.51	1.07
Olorunshogo phase 2	119.72	202.08	22,377.89	62	50.07	2.14	1.52
Sapele	193.05	454.19	38,257.67	84	52.26	2.20	1.59
Shiroro	452.53	765.67	83,904.89	83	50.45	2.57	1.87
Trans-Amadi	93.41	84.05	16,481	72	49.96	2.12	1.52
Omotosho	55.07	126.03	13,302.49	86	51.35	0.57	0.41
Ibom	79.71	93.72	14,743.85	73	50.21	2.01	1.45
Omoku	82.04	137.78	15,396.55	65	50.57	2.11	1.55
Delta	461.01	974.68	87,831.96	83	51.34	2.75	1.98

Table 2b: During Fault Peak Values at 0.061 Secs -0.4220 Secs.

Generators	Mechanical Power (MW)	Electrical Power (MW)	Terminal Current(A)	Rotor angle (Degree)	Frequency (Hz)	Exciter Current (p.u)	Exciter Voltage (p.u)
AES	202.13	201.02	10,200	25	48.51	1.23	3.23
Afam I-V	42.11	41.14	3,080.23	37	49.24	1.29	1.60
Afam VI	359.23	358.72	25,992.49	26	49.08	1.27	3.38
Egbin	772.62	770.51	53,732.21	34	48.45	1.42	5.04
Geregu	58.13	57.13	4,441.23	37	49.56	0.97	2.98
Jebba	576.14	573.22	37,873.82	38	48.66	0.57	4.94
Kainji	208.21	206.45	14,678.85	42	49.32	1.95	3.92
Okpai	146.21	150.41	9,031.28	43	49.21	1.24	3.68
Olorunshogo phase 1	46.16	45.35	3,285.72	37	48.23	1.42	2.97
Olorunshogo phase 2	103.21	101.45	6,505.20	22	48.67	1.32	3.61
Sapele	158.22	161.97	10,540.02	45	49.23	0.31	2.84
Shiroro	371.05	369.06	24,320.26	43	49.21	1.74	3.98
Trans-Amadi	74.28	72.15	4,763.4	34	49.23	1.53	3.08
Omotosho	43.19	42.21	2,986.23	32	49.15	1.48	1.08
Ibom	63.24	61.29	4,273.58	32	48.56	1.26	3.35
Omoku	64.24	63.21	4,449.87	28	50.00	1.72	2.97
Delta	376.21	372.25	24,900.48	30	49.54	1.98	3.82

 Table 2c:
 After fault (Stability with Damped Oscillation).

allowable tolerable frequency limit of 48.45 Hz-51.45 Hz at nominal frequency of 50 Hz. Moreso, the net power (difference between electrical and mechanical power) is small and the rotor angle is within 90 degrees, thus satisfying stability criteria. During the fault (0.061 secs-0.042 secs), it was observed that the net power was large and the frequency was gradually moving out of its allowable tolerable limit. However, the various electrical quantities peak values indicates that if the fault is not cleared after 0.042 secs, the system become unstable and loss synchronism between the generators, that will eventually lead to system collapse as shown in Figures 4-13. Egbin had its electrical and mechanical power before the fault to be 788.42 MW and 788.50 MW, while during the fault to be 938.23 MW and 1596.65 MW respectively. Generators that were majorly affected are Omotosho, Sapele, AES and Delta stations. The bus voltages connected to these stations, were deviating from the statutory limit of 313.45 KV-346.5 KV at 0.042 secs until the oscillation was damped. Their bus voltage values after 0.042 secs are Omotosho (361.42 KV), Sapele (358.42 KV), AES (350.43 KV) and Delta (364.32 KV). These values are as a result of the three-phase fault in the network. The buses connected to the other generating stations were however not affected.

Conclusion/Recommendation

Transient stability study of the Nigeria 330 KV integrated power network consisting of Seventeen (17) generating stations, Fifty Two (52) buses and 64 Transmission lines was carried out using ETAP 4.0 Transient analyzer. The impact of three phase short circuit fault of the largest power station (EGBIN) on the entire system stability was considered. The system was analyzed before, during and after the fault. It was observed that before the fault (0.000-0.0060 secs), the system was still stable until it got to 0.042 sec. At this time, four generating stations (Omotosho, Sapele, AES and Delta) were almost getting out of synchronism. However, when the fault was cleared, the system returned to its stability. The obtained result showed that the fault when allowed to last beyond 0.042 seconds causes buses connected to four (4) generating stations (AES, Sapele, Delta and Omotosho) to swing away from the stability region hence operating outside the allowable tolerable voltage limit of 314.45 KV-346.45 KV.

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Page 11 of 11