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Application of Synchronous Power Coefficient to Assess Steady State Stability in a Multi-Machine Power System

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Abstract Operation of interconnected power system network involves connection of many generators. It is required that all the generators must remain synchronized at all times when operating within their rated capacity. Unabated continuous grow in system loading may lead to machine running out of synchronism. This paper assessed steady state stability of power system employing synchronous power coefficient (SPC) using the Nigerian 28-bus, system. Variation in system loading will result in variation of output power for each generator. SPC is the criterion that determines whether generators remain in synchronism whenever there is a variation in load using the kinetic energy stored in its rotating masses. It is a measure of safety of operation of power system steady state stability (SSS). To determine the SPC, power flow was carried out using Newton-Ralphson method with varying loads. The reduced admittance matrix (RAM) for Y_{GG} was formulated from the bus admittance matrix. The voltages behind steady state reactance of the generators were determined and used in conjunction with RAM to determine power transfer between generator-generator. Power flow was repeated with variation of loads in step of 30%. SPC was simulated with consideration of 130%, 160% and 190% of active load. Utilizing MATLAB programming language, the results revealed that the system is stable for 130% and 160% load variation and unstable when 190% of rated load is suddenly applied to the network. This work is a pointer to the percentage of sudden load that can be connected without the system running out of synchronism

Keywords: Admittance matrix, Dead-band, Matrix elimination, No-load, Synchronous power coefficient, Transfer function

I. Introduction

Power system consists of parallel operation of many generators to serve the load of all consumers and to provide an efficient and uninterrupted power supply. Since consumer loads continue to grow unabated, the configuration of power system is becoming complex. When load is added to the system, the operating points of the system would change. Steady state stability (SSS) is the attribute of the power system which enables it to develop restoring forces between the elements equal to or greater than the disturbing forces so as to restore a state of equilibrium between the elements and hence, returning to a condition where the operation is again steady. Each of the generators that are connected together must fulfill all the conditions for parallel operation [1]. When any of these conditions is derailed by any of the generators, such generator will run out of step with the others and should therefore

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be shut down from the system immediately. One of the conditions that can cause any machine running out of step with the others is the load that is placed on it. Under the steady state operation of power system, the electrical output power is equal to the mechanical input power. However, when load changes occur in the power system operation, the rotor of the machine will experience oscillatory behaviour about the operating point [2]. The power contributed to the system by each synchronous generator is determined by the mechanical shaft power with no respect to excitation current. On the other hand, excitation current determines the power factor of the machine without affecting the active power [3] [4]. For a synchronous generator to generate more active power to the system, the governor must open the valve to admit more working fluid into the turbine couple to the generator. This will make the power angle to increase. If the change of active power with respect to change of power angle for a particular generator is less than zero ($\frac{\partial P}{\partial \delta} < 0$), it follows that the additional load placed on it is greater than the corresponding output power generated and such generator will run out of synchronism and should be shut down.

Normally, generator should be started on no-load, thereafter the load is added gradually and in steps to reach its rated output. As the load is gradually connected to each generator, its generated output gradually increases in steps with the load addition. The change in output power of the generator is accompanied with change in load angle of the rotor. The change in output power generated to the change in load angle of the rotor ($\frac{\partial P}{\partial \delta}$) of a generator is described as synchronous power coefficient (SPC). Whenever load is added to a generator, its output is a function of its governor droop characteristics. This involves exerting control on the real power exchange through outgoing lines. Active power in the power system is controlled by controlling the driving torque of the individual turbine within the system. Speed governing system exerts control over the position of valves (thermal unit) or gate (for hydro unit) and that controls the flow of working fluid through the turbine which through the electromechanical mechanism determines the generator active power output.

The governor opens the inlet valve to admit more working fluid and get a change in the active generation. A dead-band exists in the operation of governing system. Dead-band is due to the inertial of the system and friction in the bus. Dead-band is a measure of sensitivity to speed change. During dead-band duration, the governor adjusts its operation and opens the valve to admit more fuel in order to increase the machine output. During this time, the inertial of the system keeps the machine running. SPC describe the time interval during which an electrical generator can supply its rated power using the kinetic energy stored in its rotating masses. It is a function of the product of the dead-band and the change in load at any given time. For a generator to remain in synchronism within the system, the energy stored in the rotating masses before load addition should be greater (positive) than the energy loss (negative) during the dead-band and hence the SPC must give a positive value. Otherwise, it runs out of synchronism.

Many methods have been used for power system voltage stability using various stability indexes [5-7]). They give insight of closeness of the system to instability with no consideration to energy stored in the rotating masses prior to load addition. Since generators are the components of the power system that actually generate power for consumers, hence, it remains the foundation of the power system and must not be allowed to operate in catastrophic conditions. Hence, this study considers power system stability by focusing on active power compensation of generator by analyzing the disturbing and restoring forces when load is added to the system with consideration of energy stored in the rotating masses during and after load addition.

This paper has the following structure: section one gives a detail introduction of the article, section two presents materials and method with regards to power flow equations, matrix reduction and kinetic energy stored in the rotating masses of the generators while section three presents results and discussion. Conclusion and the propose direction of future research work are presented in section four.

Many authors have contributed to power system stability study. The authors in [8] presented the concept of synchronous stability in the power electronic-based network by using phase locked loop (PLL). It was discovered that the PLL output angle plays an active role in the system synchronization. But there exists steady state error between the PLL device output and the terminal voltage angle. In the study presented in [9][10] Voltage stability was enhanced by using autotransformer, additional parallel transmission lines and static synchronous series compensator for Nigerian power network using neplan application software. These methods provide reactive power compensation much more than active power compensation. FACTs devices are used for system voltage stability. Many of the FACTS devices are connected in shunt or in series either without storage element or with storage element for effective compensation.

These methods mention above provide more reactive power compensation than active power compensation and sensitive to voltage dip without any regard to system generators. FACTs devices methods introduce harmonics components into power system operation. But Changes in load affects active power flow more than the reactive power flow. Hence, the active power flow is used as a measure of stability in power systems [11][12]. Therefore, active power compensation method is very relevant in power system that involved load variation. This article study power system stability using synchronous power compensator

II. Materials and Methods

A. Active and reactive power in the power system operation is given by (1) and (2) respectively [6].

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\cos(\delta_k - \delta_i + \theta_{ik}) \tag{1}$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\sin(\delta_k - \delta_i + \theta_{ik}) \tag{2}$$

where $i = 1, 2, ..., n$ and is the number of buses

In matrix form, (1) and (2) can be expanded in Taylor's series which form the basis for the Newton-Raphson method of solving power flow problem. This is indicated in (3)

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J]\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{3}$$

where J is the Jacobian matrix of the network and is expressed as in (4) [6]

$$J = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \tag{4}$$

The elements of J in (5) gives the linearized relationship between small changes in voltage angle and voltage magnitude with the small changes in real and reactive powers respectively [13]. Change in voltage angle is proportional to changes in load while change in voltage magnitude is proportional to changes in excitation.

The superscripts indicate the number of iteration and change with each iteration. The equation (5) is a square matrix, called the Jacobian matrix and its elements are found by partial differentials of equations.

All the elements of the admittance matrix, also known as Y BUS, is equal to zero when (i ≠ k).

In a large power network, each bus is connected only to a few other buses (two or three) [14].

The Jacobian matrix of equation (5) is partitioned to emphasize the different types of partial derivatives in each sub-matrix.

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_6^{(k)} \\ \cdots \\ \Delta Q_2^{k} \\ \vdots \\ \Delta Q_6^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_6} & \vdots & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_6|} \\ \vdots & \ddots & \vdots & & \vdots\ \vdots & \ddots & \vdots \\ \frac{\partial P_6^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_6^{n}}{\partial \delta_6} & \vdots & \frac{\partial P_6^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_6^{(k)}}{\partial |V_6|} \\ \cdots & \cdots & \cdots & \vdots & \cdots & \cdots & \cdots \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_6} & \vdots & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_6|} \\ \vdots & \ddots & \vdots & & \vdots\ \vdots & \ddots & \vdots \\ \frac{\partial Q_6^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_6^{(k)}}{\partial \delta_6} & \vdots & \frac{\partial Q_6^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_6^{(k)}}{\partial |V_6|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_6^{(k)} \\ \cdots \\ \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_6^{(k)}| \end{bmatrix} \quad (5)$$

B. Matrix Reduction

Power system stability is between system generators, so the admittance matrix will be reduced to generator-generator using matrix reduction method. In matrix reduction, all statics loads are considered to be constant impedance and should be converted to admittance for power system stability study.

Since stability is the ability of the generators to hold together. Therefore, eliminate all non-generator buses from the admittance matrix.

Partitioning the admittance matrix into sub matrix, Y_{AA} (generator-generator buses), Y_{AB} (generator-load buses), Y_{CD} (load-generator buses) and Y_{DD} (load-load buses). All these sub matrixes are square matrixes.

Assuming generator buses have injected current represented by I_S while non-generator buses have 0 injected current. The matrix equation is presented in (6) as

$$\begin{bmatrix} I_S \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{AA} & Y_{AB} \\ Y_{CD} & Y_{DD} \end{bmatrix} \begin{bmatrix} V_S \\ V_X \end{bmatrix} \quad (6)$$

$$I_S = Y_{AA} V_S + Y_{AB} V_X \mathrm{Is} \quad (7)$$

$$0 = Y_{CD}\, Vs + Y_{DD}\, Vx \quad (8)$$

We eliminate non-generator voltages i.e. Vx

$$I_S = [Y_{AA} - Y_{AB} Y_{DD}^{-1} Y_{CD}] V_S \quad (9)$$

So the new Y-matrix which does not include a non-generator buses is given in (10)

$$Y_{NEW} = [Y_{AA} - Y_{AB} Y_{DD}^{-1} Y_{CD}] V_S \quad (10)$$

C. Kinetic Energy Stored in the Rotating Masses of Generator

Stored Kinetic Energy (K.E) in generator at normal speed is given in (11)

$$K.E_1 = \frac{1}{2} I\omega_1^2 \quad (11)$$

where I is the moment of Inertia, ω_1 is angular velocity at no load.

In general, stored energy is proportional to the square of the speed or square of the frequency.

$\omega = 2\pi f$

At nominal speed $K.E = \frac{1}{2} I\omega_1^2$ = GH (Joule) (12)

Where G is the machine rating, H is machine inertia.

$$\therefore K.E_1 = GH \text{ (J)} \quad (13)$$

When load (L) is suddenly applied to the machine with dead-band (d),

The energy (E) consumed by the load is given by

$$E = Ld \text{ (J)} \quad (14)$$

The remaining stored energy in the machine is given by

$$K.E_2 = GH - LD \text{ (J)} \quad (15)$$

Given that the stored energy is proportional to the square of the speed

$$\therefore K.E_1 - K.E_2 = a\omega_2^2 \quad (16)$$

where ω_2 is the new speed

$$\frac{K.E_1}{K.E_2} = \frac{\omega_1^2}{\omega_2^2} \quad (17)$$

$$\therefore \omega_2 = \omega \sqrt{\frac{K.E_2}{K.E_1}} \quad (18)$$

The active power can be shown graphically as in Fig. 1.

Any change in system loading affects the displacement of rotor angle. When the system is operating within the region OA of Fig. 1, any increase in system load is matched by an increase in the active power from the generator hence, $\frac{dP}{d\delta}$ (synchronous power coefficient) is positive and the system is said to be stable and remain synchronized. At point A, the generator active power is constant, then $\frac{dP}{d\delta}$ is zero. In the region AB, any increase in system load is accompanied by a decrease in the active power from the generator, therefore $\frac{dP}{d\delta}$ is negative. and the system becomes unstable and run out of synchronism.

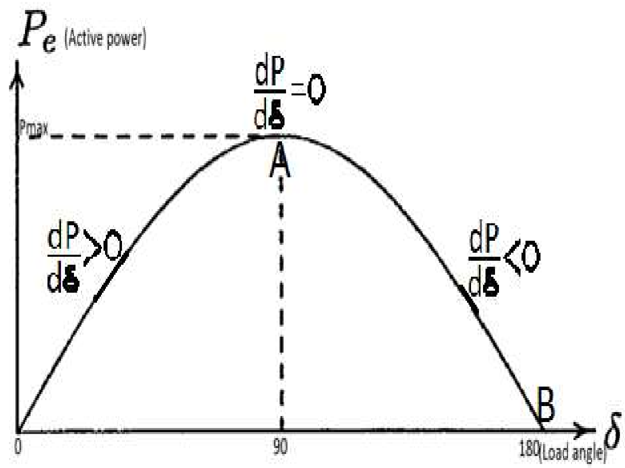

Figure 1: Representation of Power Flow

III. Results and Discussion

A. The Nigerian 28-bus 330 kV Sample Network

It contains nine (9) generator buses which include three hydro (Kainji, Jebba and Shiroro) power stations and six (6) thermal (Egbin, AES, Sapele, Okpai, Afam and Delta) power stations, forty-seven transmission lines and nineteen load buses. Egbin is used as the slack bus. Power flow result of original network is presented in Table 1

Table 1 gives the Power flow results for a base case Nigerian 28-bus 330 kV Network. Table 2, Table 3 and Table 4 give the power flow with increased loading of 130%, 160% and 190% respectively. Table 5, Table 6, Table 7 and Table 8 present SPC with base case, 130%, 160% and

190% loading respectively. It is deduced from the results that the system remains stable for the base case, 130%, 160% respectively. Though, the values of SPC increase gradually but still in synchronism. This indicates that the kinetic energy stored in the rotating masses is enough to compensate for the energy demanded from the system during the short interval of the dead-band. Table 9, which shows the SPC results for 190% load addition, indicates instability of the system. This indicates that the disturbing force is greater than the restoring force.

Table 1: Power Flow Results With base case Load.

BUS NO	V(P.U)	BUS NO	V(P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)
2	1.05	8	1.05	14	1.04	20	1.01	26	0.86
4	1.05	10	1.04	16	0.99	22	0.87	28	1.02
6	1.05	12	1.03	18	1.04	24	0.91	25	0.96
1	1.05	7	1.05	13	1.04	19	0.92	27	0.94
3	1.05	9	1.05	15	1.03	21	0.99		
5	1.05	11	1.02	17	1.02	23	1.04		

Table 2: Power Flow Results With 130% Load.

BUS NO	V(P.U)	BUS NO	V(P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)
2	1.05	8	1.05	14	1.02	20	.99	26	0.96
4	1.05	10	1.03	16	0.99	22	0.98	28	0,97
6	1.05	12	1.02	18	1.01	24	0.98	25	0.98
1	1.05	7	1.05	13	1.03	19	0.96	27	0.95
3	1.05	9	1.05	15	1.02	21	0.99		
5	1.05	11	1.01	17	1.02	23	0.97		

Table 3: Power Flow Results With 160% Load.

BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)
2	1.05	8	1.05	14	0.96	20	0.97	26	0.98
4	1.05	10	1.01	16	0.98	22	0.97	28	0.97
6	1.05	12	0.97	18	0.97	24	0.98	25	0.95
1	1.05	7	1.05	13	0.95	19	0.99	27	0.96
3	1.05	9	1.05	15	0.97	21	0.98		
5	1.05	11	0.98	17	0.96	23	0.96		

Table 4: Power Flow Results With 190% Load.

BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)	BUS NO	V (P.U)
2	1.05	8	1.03	14	0.96	20	0.95	26	0.98
4	1.05	10	0.94	16	0.98	22	0.95	28	0.95
6	1.04	12	0.93	18	0.98	24	0.98	25	0.97
1	1.05	7	1.03	13	0.94	19	0.98	27	0.96
3	1.05	9	1.05	15	0.97	21	0.95		
5	1.05	11	0.95	17	0.97	23	0.94		

Table 5: Synchronous Power Coefficients with Base Case Load for Nigerian 28-bus 330kV Network.

2.747	0.880	7.469	0.620	0.217	11.76	0.031	92.85
2.747	3.400	2.225	0.185	0.106	124.8	0.127	3.678
0.880	3.400	0.713	0.059	5.299	14.56	14.943	1.178
7.469	2.225	0.713	121.9	40.44	9.529	0.026	9.997
0.620	0.185	0.059	121.9	3.366	0.793	0.002	0.832
0.217	0.106	5.399	40.44	3.366	0.455	5.514	0.281
11.76	124.8	14.56	9.529	0.793	0.455	0.546	15.75
0.031	0.127	14.94	0.026	0.002	5.514	0.546	0.044
92.85	3.678	1 1.178	9.997	0.832	0.291	15.75	0.044

Table 6: Synchronous Power Coefficients with 130% Loading for Nigerian 28-bus 330kV Network.

2.748	0.880	7.469	0.621	0.217	11.77	0.033	92.85
2.748	3.400	2.225	0.185	0.106	124.8	0.127	3.678
0.880	3.400	0.713	0.059	5.299	14.56	14.943	1.178
7.469	2.225	0.713	121.9	40.44	9.529	0.026	9.997
0.217	0.185	0.059	121.9	3.366	0.793	0.002	0.832
11.77	0.106	5.399	40.44	3.366	0.455	5.514	0.281
11.77	124.8	14.56	9.529	0.793	0.455	0.546	15.75
0.033	0.127	14.94	0.026	0.002	5.514	0.546	0.044
92.85	3.678	1 1.178	9.997	0.832	0.291	15.75	0.044

Table 7: Synchronous Power Coefficients with 160% Loading for Nigerian 28-bus 330kV Network

1.437	0.712		2.304	0.621	0.122	2.340	0.033	41. 415
1.437	2.241		2.123	0.185	0.106	124.8	0.127	3.678
0.712	2.241		0.432	0.056	5.299	14.56	14.943	1.178
2.304	2.123		0.432	80.9	21.340	9.529	0.026	9.997
0.621	0.185		0.056	80.9	1.264	0.793	0.002	0.832
0.122	0.106		5.399	21.340	1.264	0.203	5.514	0.281
2,340	124.8		14.56	9.529	0.793	0.203	0.135	15.75
0.033	0.127		14.94	0.026	0.002	5.514	0.0,135	0.012
41.415	3.678	1	1.178	9.997	0.832	0.281	15.75	0.012

Table 8: Synchronous Power Coefficients with 190% Loading for Nigerian 28-bus 330kV Network

1.247	0.880		7.469	-0.621	0.217	11.77	-0.033	92.85
1.247	1,203		2.225	0.185	-0.106	124.8	-0.127	3.678
0.880	1.203		0.521	0.059	5.299	14.56	14.943	1.178
7.469	2.225		0.521	58.101	40.44	9.529	0.026	9.997
-0.621	0.185		0.059	58.901	1,286	0.793	-0.002	0.832
0.217	-0.106		5.399	40.44	1.286	0.455	5.514	-0.281
11.77	124.8		14.56	9.529	0.793	0.455	0.245	15.75
-0.033	-0.127		14.94	0.026	-0.002	5.514	0.245	0.032
92.85	3.678	1	1.178	9.997	0.832	-0.281	15.75	0.032

IV. Conclusion

The Nigerian power network of 28-bus, 330-kV transmission line consisting of nine generating stations with three hydro power stations and six thermal power stations was analyzed to determine its SSS using SPC method. Starting with a base case active power P of the generator given by $P_{min} \leq P \leq P_{max}$, gradual load additions were carried out in step of 30% . All the values of SPC indicate that the system is stable with 130% and 160% loading. But the system becomes unstable when the load was increased to 190%. Direction of further study is determination of critical clearing time (CLT) for the generator that causes lack of synchronism to be identified.

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