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Full Length Research Paper

Low-frequency power oscillation damping enhancement and voltage improvement using unified power flow controller (UPFC) in multi-machine power system

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The problem of low-frequency power swings is a matter of concern for power systems engineers in the operation and planning of power systems. Therefore, this paper is an investigation of the use of unified power flow controller (UPFC) that is suitably tuned to improve the damping of low frequency power oscillations present in Nigerian grid system. A large disturbance is initiated, during simulation in PSAT, in the network to induce nonlinear oscillations of the power system in order to ascertain the damping effect of UPFC. The dynamic responses of the system simulated show that the system is well damped and is stabilized at minimal time which confirms the robustness of the UPFC. Finally, a comparative study in a typical transient stability problem on IEEE 14-bus system using a UPFC model and the Nigerian high voltage interconnected system is used to illustrate the concepts presented in this paper.

Key words: Power oscillation damping, power systems, unified power flow controller (UPFC), flexible AC transmission system (FACTS) devices, low frequency oscillation.

INTRODUCTION

The problem of low-frequency power swings is a matter of concern for power systems engineers. As it is becoming increasingly important to fully utilize the existing transmission system assets, proper attention should be given to the enhancement of utilizing the transmission capacity by damping of the power swings. Flexible AC transmission system (FACTS) devices are found to be very effective for this purpose (Hingorani, 1999). A FACTS device should have an adequate margin of variable compensation for effective damping of power swings. Therefore, while planning for FACTS controllers, the damping effect per MVar and the control cost should be taken into consideration (Mhaskar, 2006). The damping provided by FACTS devices offers the means to reduce the inhibiting effects of the oscillations or swings. But the outputs of these FACTS devices should be restricted by the limits within their working conditions. Notwithstanding, low frequency oscillations are detrimental to the goals of maximum power transfer and optimal power system security.

Unified power flow controller (UPFC) is a member of FACTS family. It is a combination of Static synchronous compensator (STATCOM) and Static synchronous series compensator (SSSC) coupled via a common dc-link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The UPFC, by means of angularly unconstrained series voltage injection, is able to control the transmission line voltage, impedance and angle or the real and reactive power flow in the line (Uzunovic et al., 1999).

However, some works have been done on various studies and applications of the UPFC using different tools and models, and are documented in literature by some authors. The authors, Padiyar and Kulkarni (1998) proposed a control strategy for the UPFC and, in its power oscillation damping control mode, evaluate the results by simulating in SIMULINK. In Mihallic et al. (1996), the authors analyzed the effect of the UPFC on transient stability margins of a power system and explicit

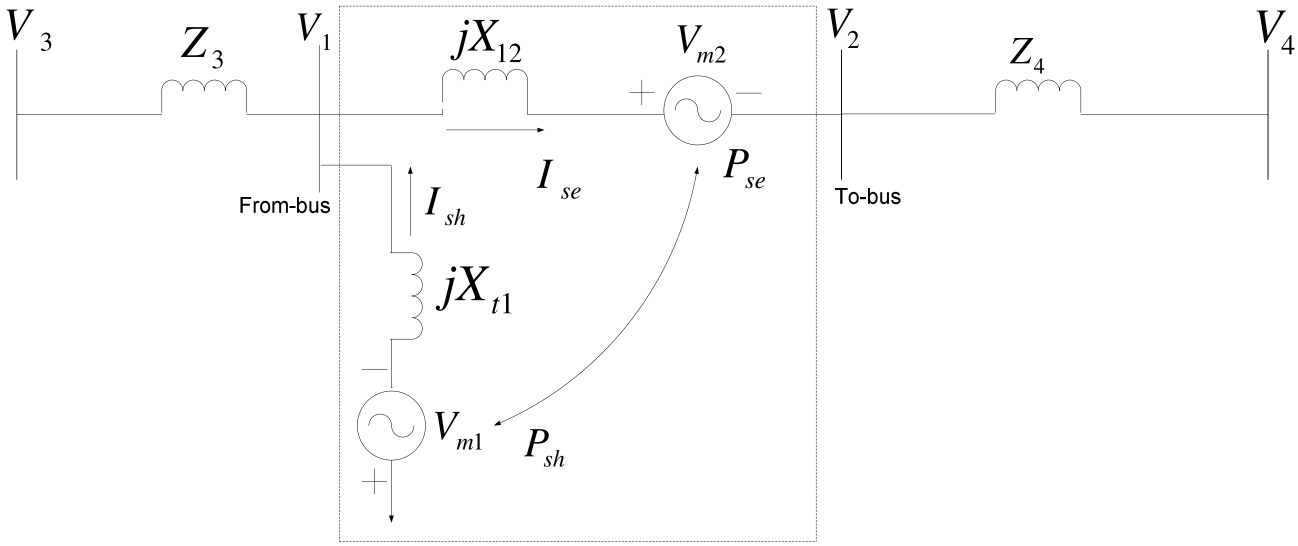

Figure 1. Model of UPFC.

results are shown by simulation in NETOMAC (a simulation program). Schauder et al. (1998) illustrate the operation of the UPFC under fault conditions and the authors, Lerch et al. (1994) further stressed the effect of UPFC in the steady-state and dynamic operation of a simple interconnected power system using the stability mode of NETOMAC.

This paper investigates the use of UPFC that is suitably tuned to improve the damping of low frequency oscillations present in Nigerian grid network in extreme operating conditions and evaluate the results by simulating in PSAT (Federico, 2005). The benefit of the damping of these oscillations was evident through the ability to increase the tie-line power flowing in the grid network. A large disturbance, such as a short-circuit, is initiated in the network to induce nonlinear oscillations of the power system in addition to the small-signal low frequency oscillation modes in order to ascertain the damping effect of UPFC. But the analysis of these oscillations is beyond the scope of this paper; hence, time-domain simulations will be used to verify the return to stability of the grid network after several transient events.

UPFC MODEL AND ITS CONTROL STRATEGY

The UPFC is modeled as two voltage-source inverters coupled on their DC sides through a common DC capacitor link. One inverter (shunt) is connected to the power system through a shunt transformer, whereas the other inverter (series) is inserted into the transmission line through a series transformer. The series inverter produces an AC voltage of controllable magnitude and phase angle which is injected into the transmission line through the series transformer while the shunt inverter provides the required real power at the DC terminals, so that real power flows freely between the controller shunt and series AC terminals through the common DC link. However, from the basic scheme of the model shown in Figure 1, the mathematical model can be derived with the aim of being able to study the relations between the electrical transmission system and UPFC in steady-state conditions. This figure represents a single-line diagram of a simple transmission line with impedance, UPFC, sending-end voltage source and receiving-end voltage source. According to Figure 1, the power circulation and the line flow are calculated by the following expressions (Chow, 2004):

$$P_{sh} + P_{se} = 0 \quad \text{(neglecting losses)} \tag{1}$$

$$P_L = V_2\left(V_{m2}\sin(\theta_2 - \alpha_2) - V_1\sin(\theta_2 - \theta_1)\right)/X_{t2} \tag{2}$$

$$Q_L = -V_2\left(V_2 - V_1\cos(\theta_2 - \theta_1) + V_{m2}\cos(\theta_2 - \alpha_2)\right)/X_{t2} \tag{3}$$

Due to the inherent and unique characteristics of the UPFC to independently control the real and reactive power, the control strategies of the controller can vary widely. However, in most cases, it is anticipated that the UPFC will be used to control its bus voltage by locally generating or absorbing reactive power. It can as well be used to control power flows on the transmission line by regulating the magnitude and phase shift of the series injected synchronous voltage. The strategy employed is the use of PWM switching techniques which permit independent control of active and reactive power inputs into the inverters, provided that the DC capacitor voltage is kept sufficiently high. As proposed in Papic et al. (1997), the control block diagrams shown in Figures 2a and b are used here to control both the series branch and shunt branch of the UPFC. Of course, this is based on PI controllers to independently control AC and DC voltage magnitudes.

Finally, the modulation controller of Figure 3 proposed by Padiyar and Kulkarni (1998) is used here to control the power oscillations. This control uses the slip of the desired machine Δω to modify

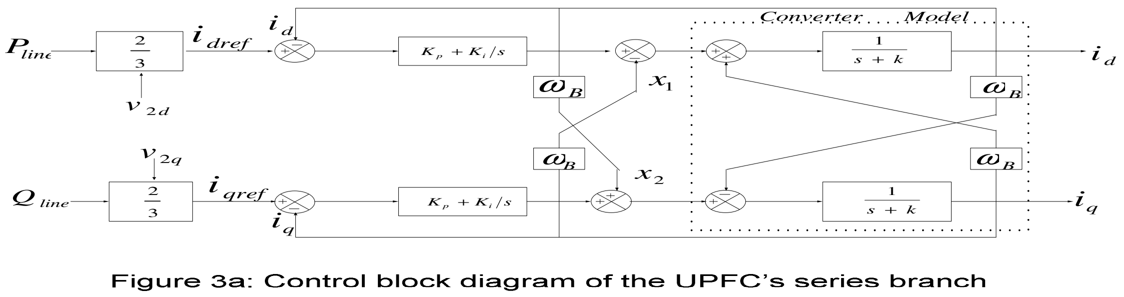

Figure 2a. Contol block diagram of the UPFC's series branch.

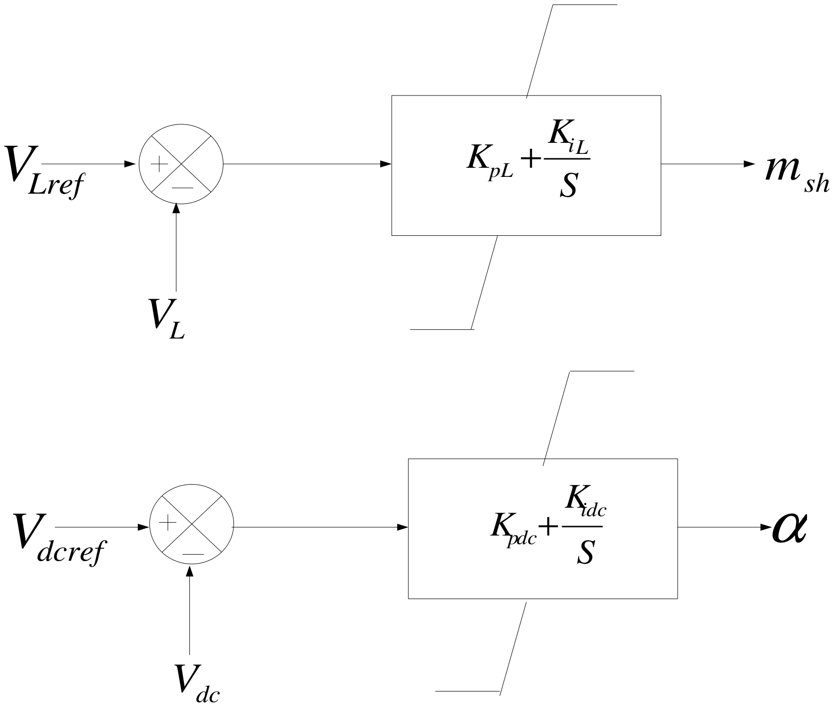

Figure 2b. Contol block diagram of the UPFC's shunt branch.

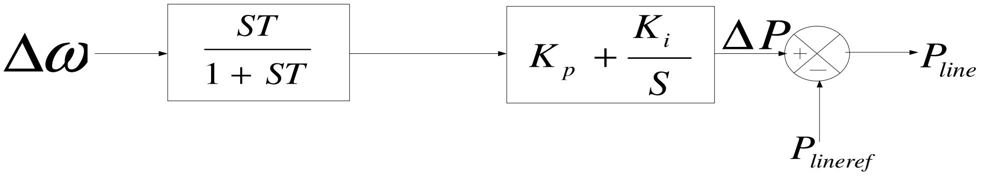

Figure 3. Power modulation control.

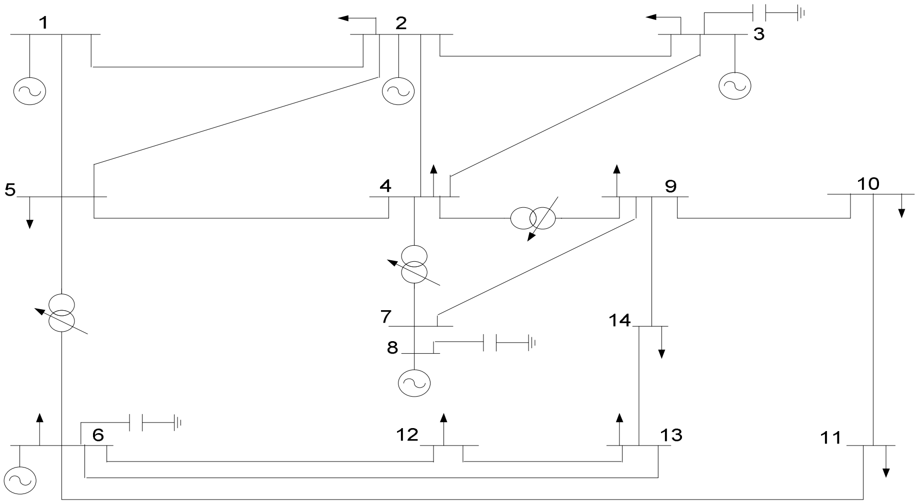

Figure 4. IEEE 14-bus system.

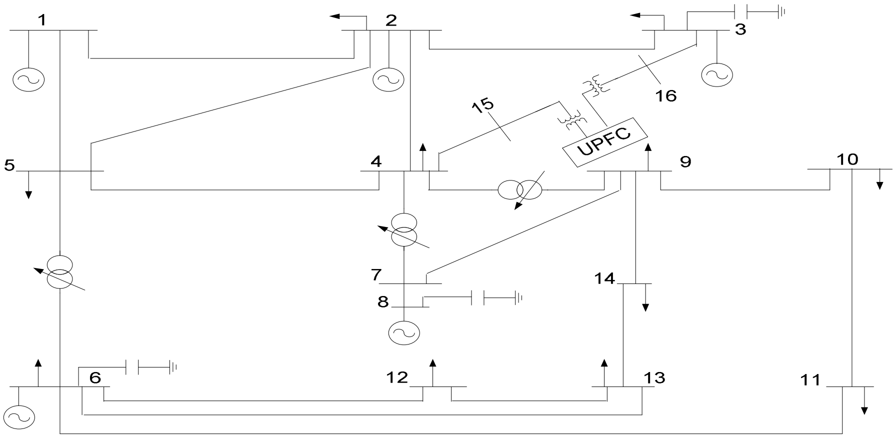

Figure 5. IEEE 14- bus system with UPFC.

the active power signal reference P_{line} on the series inverter controller.

DYNAMIC PERFORMANCE OF POWER SYSTEM WITH UPFC

Two case studies are examined to know the characteristic behaviour of the systems at various contingencies and the optimal damping behaviour when UPFC is embedded in those systems. Of course, the controller should have been properly tuned (that is, adjusting the PI parameters by multiple runs) in order to obtain optimal damping behaviour; and is operated in the power oscillation damping control mode. The selected studied systems ranging from small to reasonably large systems (Anderson, 1994) are simulated within MATLAB environment using PSAT. Subsequently, these systems - the IEEE 14-bus system and the Nigerian grid network are considered for their steady state and transient stability improvement when UPFC is optimally sited in the networks. Herein, the single line diagrams for these systems are shown in Figures 4 to 6. The line and bus data of these systems are given in Appendices 1 and 2.

Case study 1 (IEEE 14-bus system)

The performance of the UPFC is tested on this IEEE 14-bus system as shown in Figure 4. Data for the system can be found in Appendix 2. In non-linear simulations of contingencies, a fault duration was considered to assess the performance of UPFC (results are depicted under case study 1).

Case study 2 (Nigerian grid system)

The Nigerian grid network is being considered as case study 2. It is interesting to know that this system by reason of the location of its generating plants is zoned into four major areas. The four areas are interconnected with tie lines during normal operating conditions.

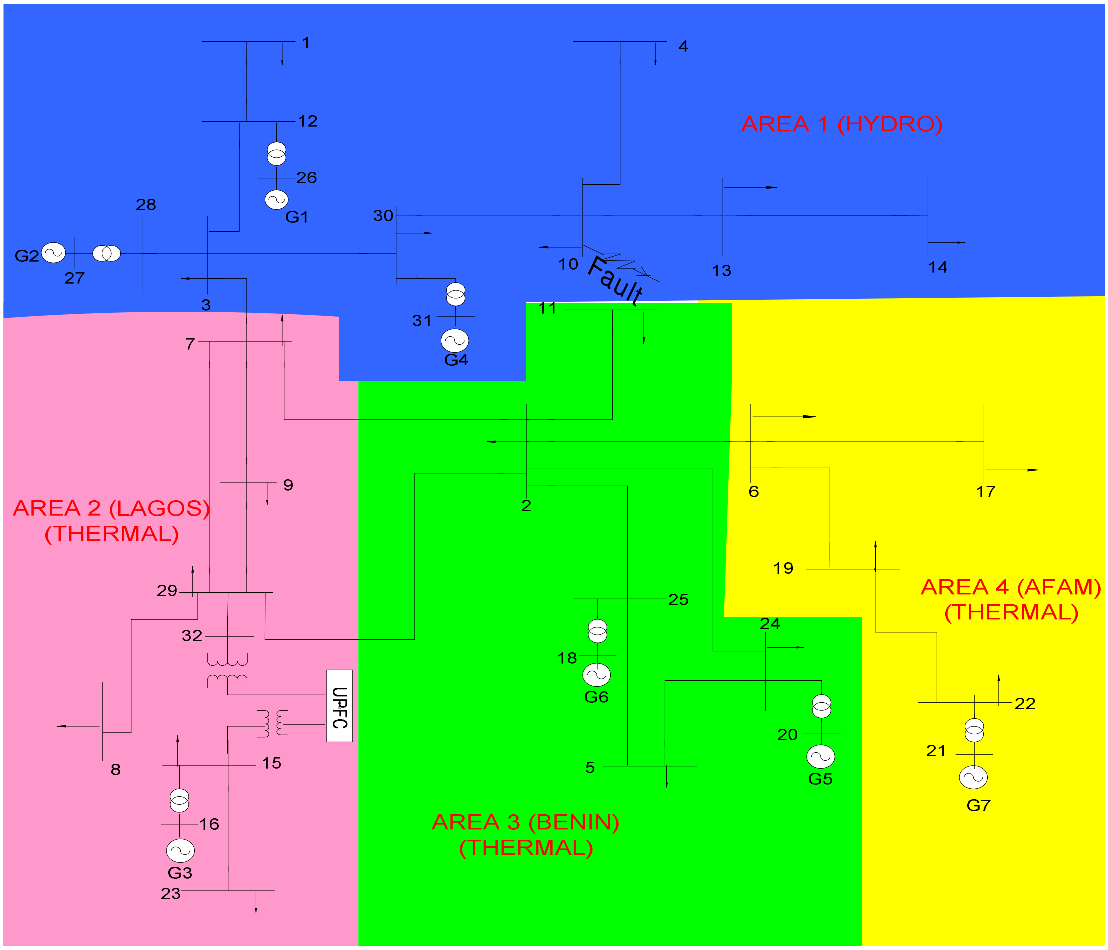

Figure 6. 7-Machine 31-bus system network for case study.

The system consists of 31 buses, 33 branches, 7 transformers and 7 synchronous machines. There are 21 loads in the system totaling 2830 MW and 1441 MVar. The dynamic data for the generators are extracted from Power Holding Company of Nigeria (PHCN). As shown in Figure 6, UPFC is included in the Nigerian grid system to reach the desired busbar voltages (V_{bus15} and V_{bus29}) and the desired line flows for the UPFC control system. At first, the power flow analysis is performed with the help of PSAT (Federico, 2005) of the power system without UPFC and considered as basis for subsequent analysis. It is observed that the voltages for busbars 15 and 29 in Figure 6 are lower compared with voltages of other busbars in the network. It is required that the busbar voltages should be 0.97 p.u. or even higher at the normal situation. Therefore UPFC is installed between busbars 15 and 29 to improve the voltages at these busbars. As the system is compensated by UPFC, the voltage profiles at various busbars below 0.97 p.u. are enhanced. However, the main focus of this research is to damp the power oscillations associated with the power generated in the Nigerian grid system by use of UPFC.

SIMULATIONS IN PSAT AND DISCUSSION OF RESULTS

Simulations of these systems are carried out with and without UPFC to determine the effect of UPFC on oscillation damping and voltage stability enhancement as it affects machine speeds, power flows between buses and voltages at various buses.

Results of case study 1

At 0.10 s fault duration, it was observed that the system without the UPFC oscillates long after the fault is cleared, whereas the desired power flow conditions are reached quickly after the fault is cleared for the system with UPFC. The power swings of the machines in IEEE 14-bus network are prominent in the speeds and rotor angles of those machines, particularly, at contingencies for instability which no sooner than the application of UPFC damps out the swings. These are depicted in Figures 7 to 11.

Results of case study 2

Nonlinear simulations of a contingency (that is,

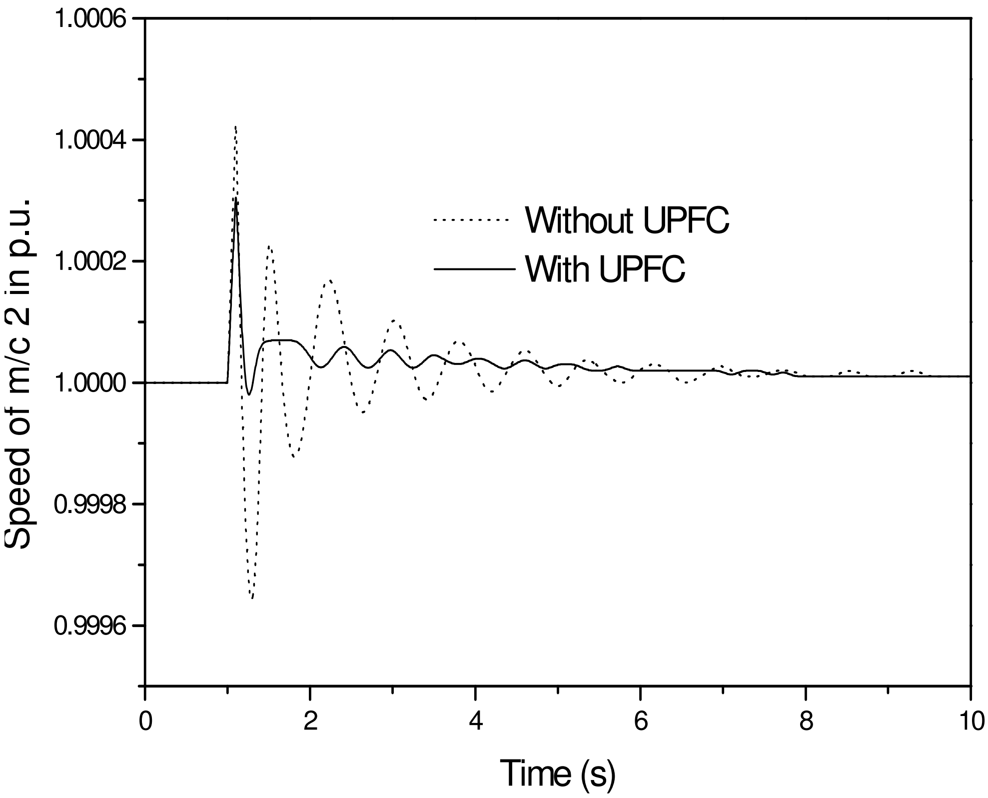

Figure 7. Speed of m/c 4 of IEEE 14-bus system.

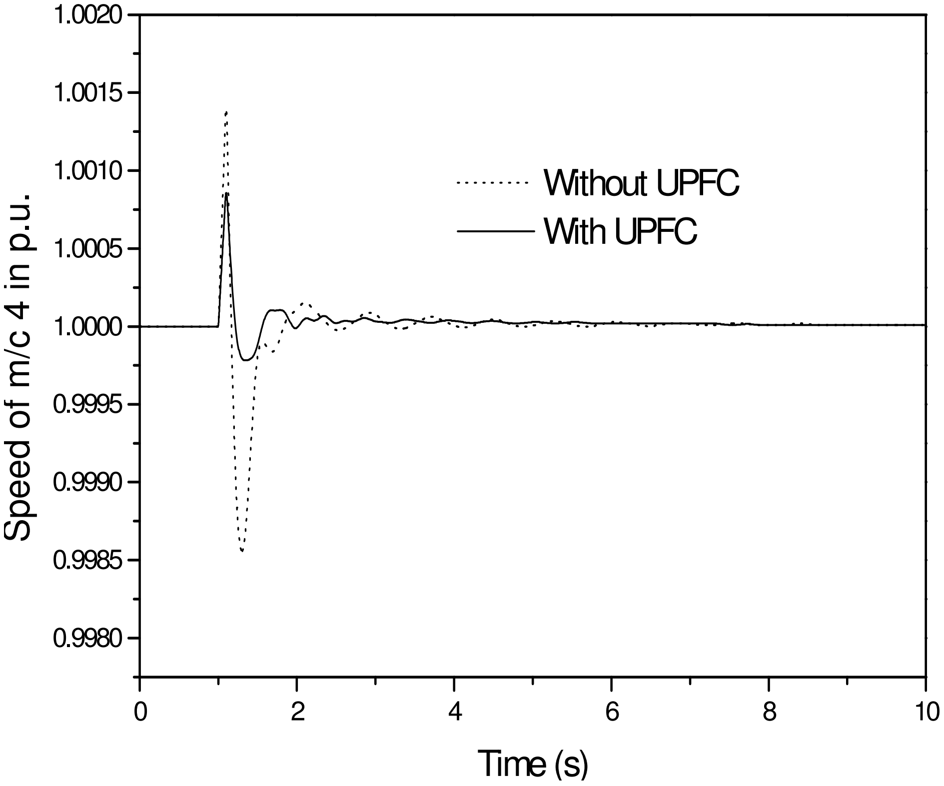

Figure 8. Speed of m/c 2 of IEEE 14-bus system.

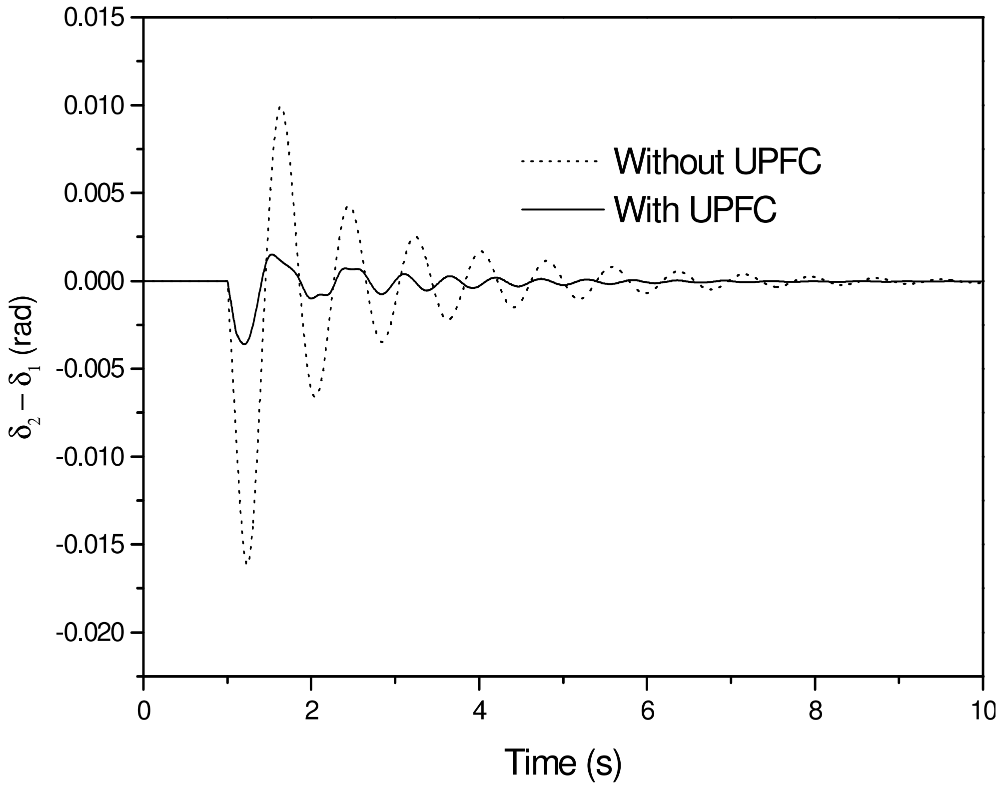

Figure 9. Rotor angle of m/c 2 of 14-bus system.

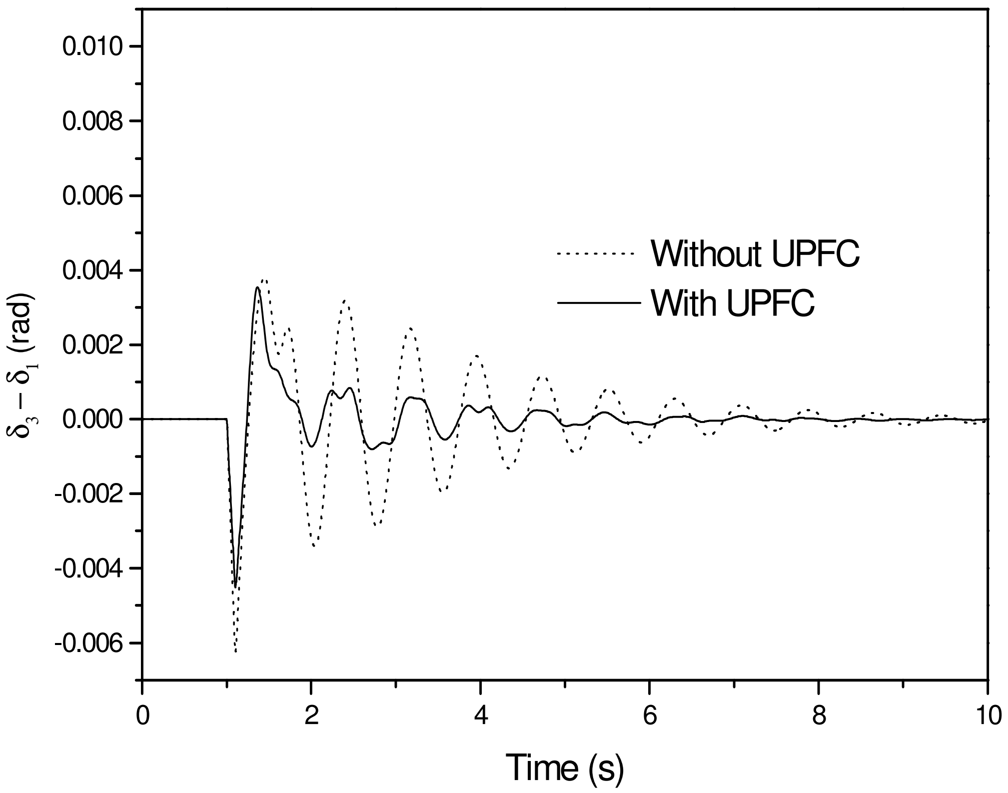

Figure 10. Rotor angle of m/c 3 of 14-bus system.

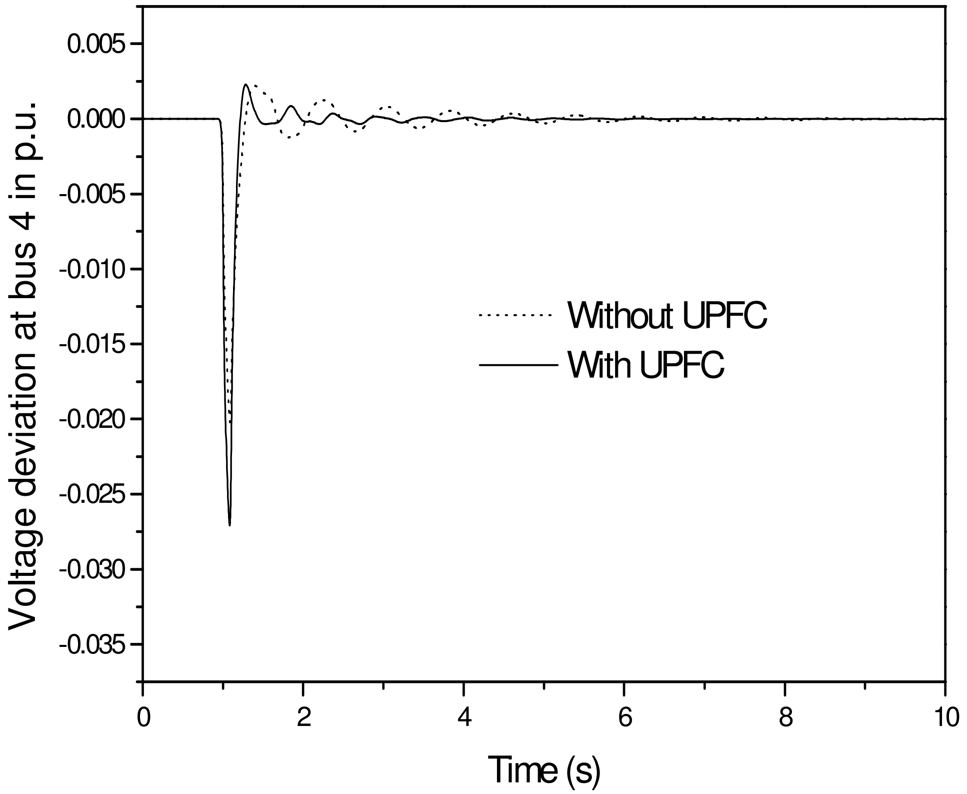

Figure 11. Voltage at bus 4 of 14-bus system.

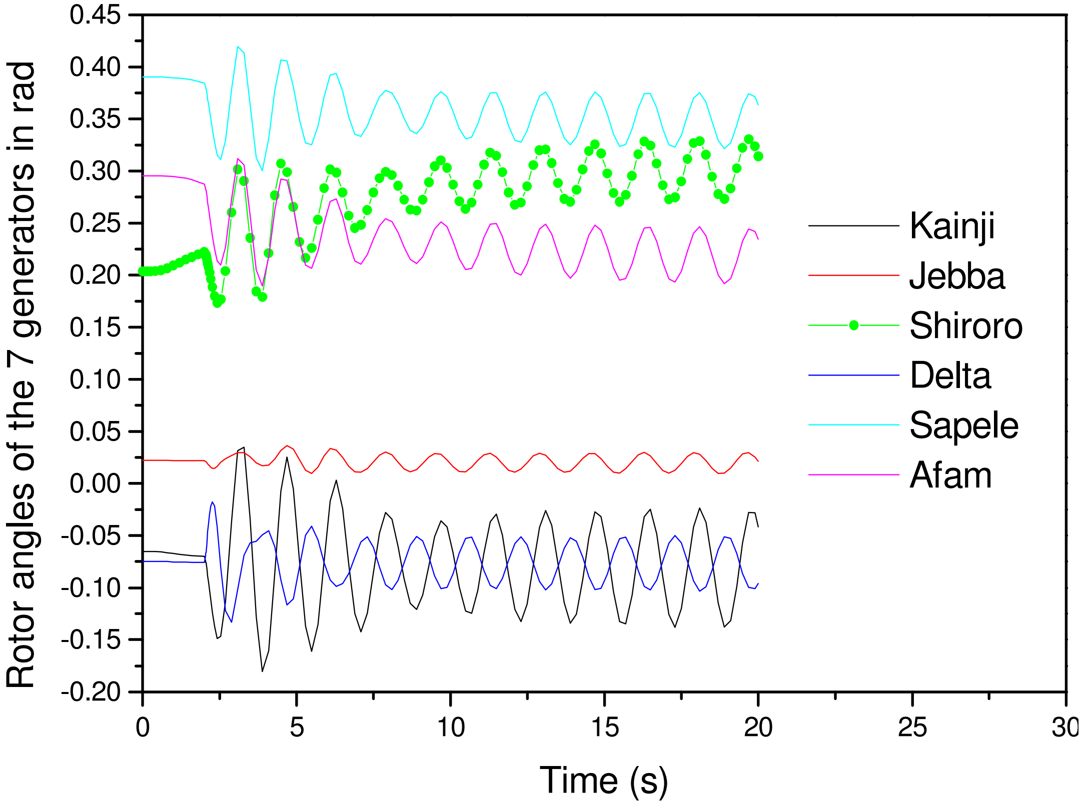

Figure 12. Rotor angles of generators in Nigerian power system network.

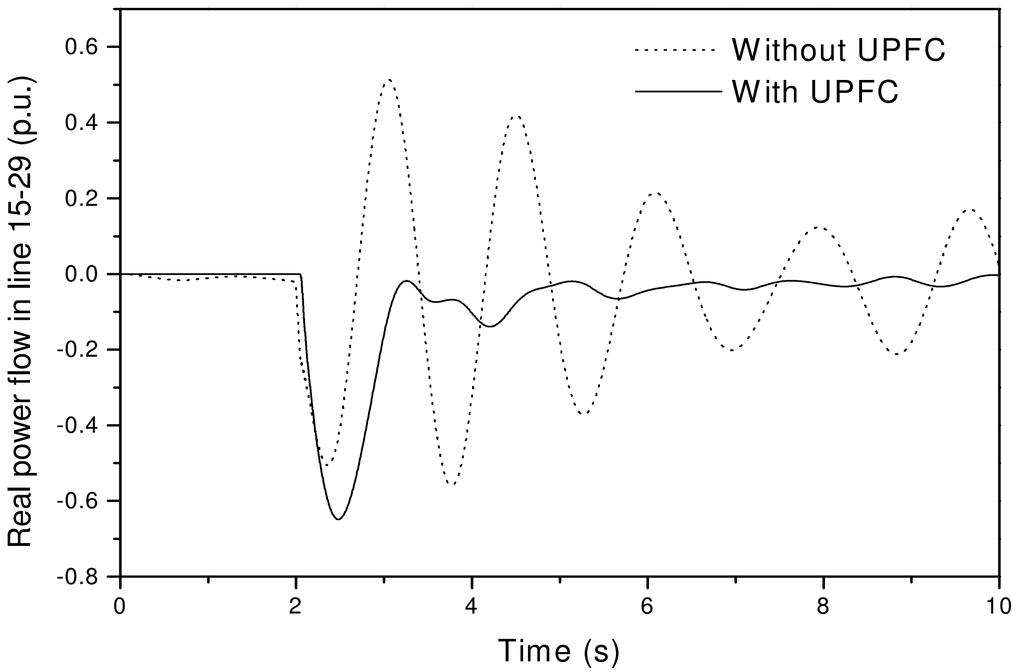

Figure 13. The damping effect of UPFC on the power flow in line 15 to 29.

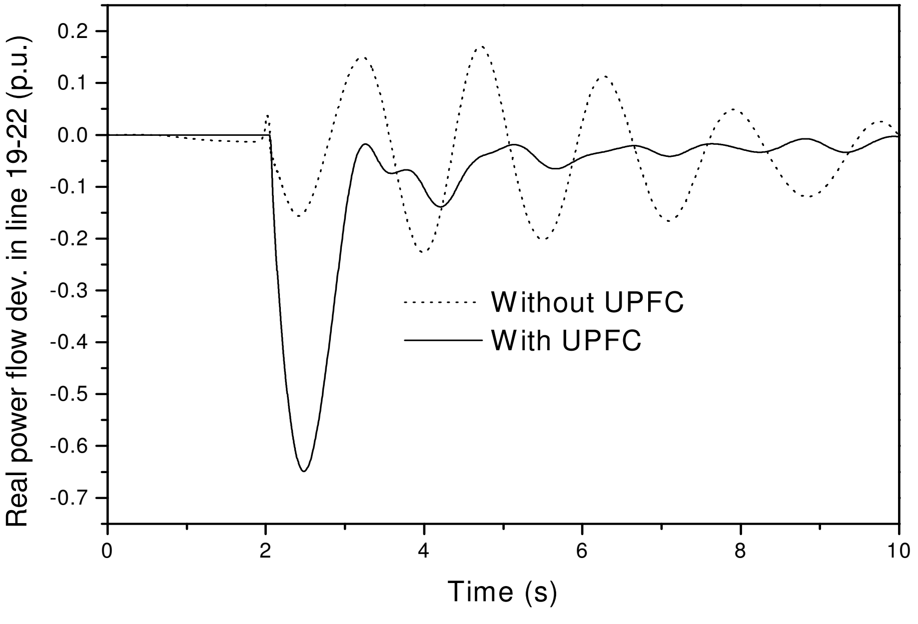

Figure 14. Real power flow in line 22 to19 of Nigerian grid system.

application of a 3-Ø fault on bus 10 at time, t = 2.0 s) are performed in the system. The instability of the system leads to the steady increase in rotor angle of Shiroro generator (though closest to the location of fault) due to lack of insufficient synchronizing torque, as shown in Figure 12.

Although UPFC is installed to damp power oscillations the place of its location, the damping effect of the UPFC can as well be noticed in all areas in the system network, though may not be as pronounced as the area where UPFC is located. To demonstrate the effectiveness of the proposed UPFC in improving the damping for the power oscillation, dynamic responses of the system are simulated and are depicted in Figures 13 to 16.

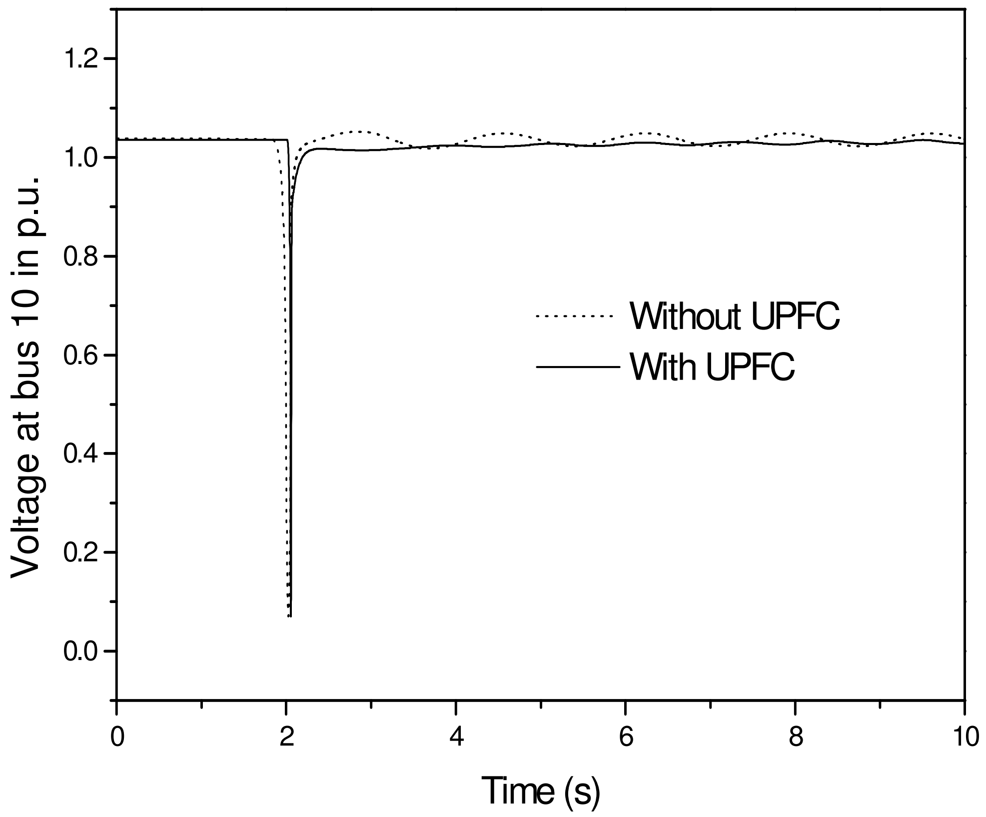

Figure 15. Voltage at bus 10 of Nigerian grid system.

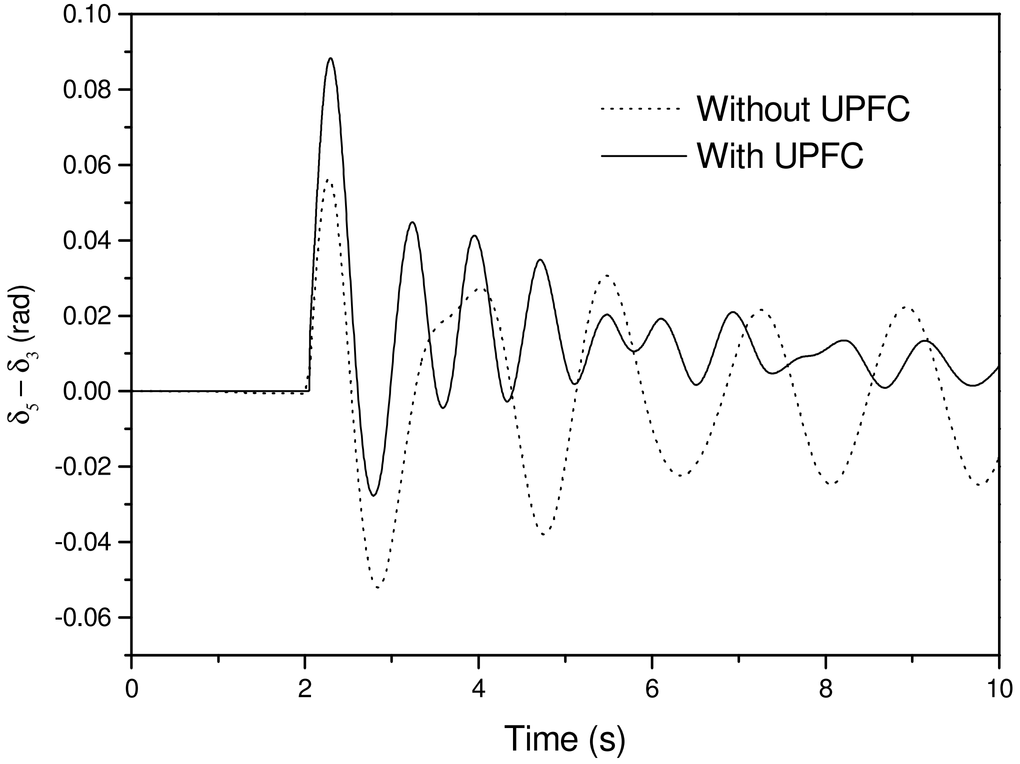

Figure 16. Rotor angle of m/c 5 of NGS.

Conclusion

This paper has presented an approach to solve stability problem using UPFC which is operated in the direct voltage injection mode. The importance of enhancing the system stability limit by damping the power oscillation using UPFC is stressed. The control strategy employed is the use of PWM switching techniques at the high voltage of DC capacitor which permit independent control of active and reactive power inputs into the inverters. Of course, in simulation, this enhances the damping of power oscillations of the Nigerian grid system and IEEE 14-bus system. The results obtained in simulations are consistent with observations made in previous studies available in the current power system stability literature and show the effectiveness of the UPFC in damping of power system oscillations. However, the damping of power oscillations could be more noticeable in IEEE 14-bus system than Nigerian grid system, perhaps, because of the complexity of the Nigerian network.

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APPENDIX 1

The electrical data of the Nigerian grid system are as stated in the tables.

Table 1. Generating units for the Nigerian grid system (330 kV).

Station	MVA	H	x_d	x'_d	x''_d	x_q	x'_q	x''_q	T'_{do}	T''_{do}	T'_{qo}	T''_{qo}	x_l	R
G7	600	3.39	0.65	0.26	0.24	0.44	-	0.24	5.2	0.06	-	0.24	0.14	0.0037
G6	450	3.34	0.75	0.28	0.21	0.53	-	0.21	6.0	0.04	-	0.16	0.16	0.004
G5	700	3.24	0.8	0.3	0.2	0.49	-	0.24	5.57	0.05	-	0.34	0.16	0.004
G4	1500	3.09	1.87	0.262	0.23	1.87	0.45	0.22	7.1	0.063	1.0	0.11	0.18	0.004
G3	550	6.70	2.16	0.234	0.17	2.16	-	0.16	8.6	0.05	-	0.20	0.12	0.002
G2	440	8.91	2.17	0.25	0.18	1.92	-	0.18	8.8	0.05	-	0.20	0.13	0.004
G1	330	9.01	2.09	0.20	0.15	1.89	-	0.15	6.93	0.05	-	0.20	0.11	0.003

Table 2. Transmission line data in p.u on 100 MVA base of Nigerian grid system (330 kV).

Line no.	From bus i	To bus j	Line parameters (P.U.)		
			R	X	B
1	1	2	0.01218	0.09163	1.02690
2	2	3	0.00159	0.01197	0.53660
3	2	4	0.00000	0.01351	0.00000
4	3	6	0.00016	0.00118	0.05300
5	3	7	0.00206	0.01547	1.56000
6	3	8	0.00480	0.03606	1.61650
7	5	6	0.00000	0.01932	0.00000
8	7	15	0.00987	0.07419	0.83150
9	7	18	0.00412	0.03098	0.34720
10	7	20	0.01163	0.08750	0.98050
11	8	9	0.00000	0.01638	0.00000
12	8	10	0.00189	0.01419	0.63600
13	10	12	0.00904	0.06799	0.76190
14	10	13	0.00774	0.05832	0.65260
15	11	15	0.00766	0.05764	0.64600
16	13	14	0.01042	0.07833	0.87780
17	15	16	0. 0538	0.04050	0.45380
18	15	20	0.00550	0.04139	1.88500
19	15	30	0.00287	0.02158	0.24180
20	15	31	0.00098	0.00739	0.33130
21	16	17	0.00377	0.02838	0.31800
22	16	19	0.00605	0.04552	0.51010
23	18	20	0.00538	0.04050	0.45400
24	19	29	0.00049	0.00369	0.16560
25	20	21	0.00036	0.00266	0.11900
26	20	22	0.00122	0.00916	0.41080
27	22	23	0.00000	0.00648	0.00000
28	22	24	0.00028	0.00207	0.09280
29	25	31	0.00000	0.01204	0.00000
30	26	30	0.00102	0.00769	0.08613
31	26	31	0.00248	0.01862	0.20870
32	27	30	0.00000	0.01333	0.00000
33	28	29	0.00000	0.01422	0.00000

APPENDIX 2

IEEE 14-bus system data

Table 1. Line data (Values in per unit; Base on 100 MVA).

From bus	To bus	R	X	$\frac{1}{2}$ line charge/X former ratio
1	2	0.01938	0.05917	0.02640
2	3	0.04699	0.19797	0.02190
2	4	0.05811	0.17632	0.01870
1	5	0.05403	0.22304	0.02460
2	5	0.05695	0.17388	0.01700
3	4	0.06701	0.17103	0.01730
4	5	0.01335	0.04211	0.00640
5	6	0.0	0.25202	0.932
4	7	0.0	0.20912	0.978
7	8	0.0	0.17615	0.0
4	9	0.0	0.55618	0.969
7	9	0.0	0.11001	0.0
9	10	0.03181	0.08450	0.0
6	11	0.09498	0.19890	0.0
6	12	0.12291	0.25581	0.0
6	13	0.06615	0.13027	0.0
9	14	0.12711	0.27038	0.0
10	11	0.08205	0.19207	0.0
12	13	0.22092	0.19988	0.0
13	14	0.17093	0.34802	0.0

Table 2. Bus data (All power values are in MW and MVar).

Bus no.	Bus type	V	Pg	Qg	Pl	Ql	Qmax	Qmin
1	3	1.060	232.4	0	0.0	0	-	-
2	2	1.045	40.0	0	21.7	12.7	50	- 40
3	2	1.010	0.0	0	94.2	19.0	40	0
4	1	1.000	0.0	0	47.8	-3.9	0	0
5	1	1.000	0.0	0	7.6	1.6	0	0
6	2	1.070	0.0	0	11.2	7.5	24	-6
7	1	1.000	0.0	0	0.0	0.0	0	0
8	2	1.090	0.0	0	0.0	0.0	24	-6
9	1	1.000	0.0	0	29.5	16.6	0	0
10	1	1.000	0.0	0	9.0	5.8	0	0
11	1	1.000	0.0	0	3.5	1.8	0	0
12	1	1.000	0.0	0	6.1	1.6	0	0
13	1	1.000	0.0	0	13.5	5.8	0	0
14	1	1.000	0.0	0	14.9	5.0	0	0

Table 3. Machine parameters.

Parameter	Mach. 1	Mach. 2	Mach. 3	Mach. 4	Mach. 5	Unit
r	0.00	0.0031	0.0031	0.0014	0.0014	p.u.
x	0.239	0.00	0.00	0.134	0.134	p.u.
T'_{do}	7.4	6.1	6.1	4.75	4.75	s
T''_{do}	0.03	0.04	0.04	0.06	0.06	s
x_q	0.646	0.98	0.98	1.22	1.22	p.u.
x'_q	0.646	0.36	0.36	0.715	0.715	p.u.
x''_q	0.4	0.13	0.13	0.12	0.12	p.u.
T'_{qo}	0.00	0.3	0.3	1.5	1.5	s
T''_{qo}	0.033	0.099	0.099	0.21	0.21	s
M	10.296	13.08	13.08	10.12	10.12	s
D	2.00	2.00	2.00	2.00	2.00	p.u.
T_{aa}	0.00	0.00	0.00	0.00	0.00	s
x_d	0.8979	1.05	1.05	1.25	1.25	p.u.
x'_d	0.64	0.1850	0.1850	0.232	0.232	p.u.
x''_d	0.23	0.13	0.13	0.12	0.12	p.u.

p.u: per unit, s: seconds.