

Optimal Location of Unified Power Flow Controller (UPFC) in Nigerian Grid System

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Abstract: This study presents an approach to find and choose the optimal location of Unified Power Flow Controller (UPFC) based on the sensitivity of the total system active power loss with respect to the control variables of the Unified Power Flow Controller (UPFC). The control system of the UPFC's injection model is developed and its contributions to avoiding a voltage collapse are explored by analyzing a multi-machine test system. With the UPFC being embedded in the system using static approach, the analysis is concentrated on the sensitivities of the UPFC's set of control parameters. The sensitivities concern minimization of total system power loss. Simulation studies are carried out in the MATLAB/Simulink environment and results show that optimal siting of the UPFC provide better damping during transient and dynamic control as well as enhance voltage stability.

Key words: UPFC, optimal siting, sensitivity analysis, grid system, FACTS devices, active power loss, voltage stability

INTRODUCTION

The problem of voltage stability with voltage collapse as its final consequence has been of great concern in power system planning and operation. Several attempts have been made to improve operating margins necessary for grid stability ranging from the conventional use of power system stabilizers to the design of power electronic equipment of high rating for high voltage systems. It is the rapid development of power electronics that paved the way for the advent of FACTS controllers which provide voltage support and regulate power flow on transmission lines. But the location of these FACTS controllers has been enormous challenge confronting the transmission utilities.

Many researches have been made on the optimal location of FACTS devices in order to improve the system dynamic behaviour, thus enhancing the system reliability. Okamoto *et al.* (1995) have indicated that the effectiveness of the controls for different purposes mainly depends on the location of the control device. Furthermore, it is impossible to perform the simulation on every bus in a large power system. So, a method should be selected to determine optimal placement of the control device. There are studies that allocate FACTS devices for damping inter-area oscillations and stability enhancement by employing eigenvalue analysis (Dizdarevic *et al.*, 1998; Dizdarevic, 2001). A modal analysis of the voltage stability has been introduced by Moghavvem and Faruque (2000) and Preedavichit and Srivastava (1998) which determines the placement of

FACTS based on participation parameter. A voltage stability index has been proposed by Palanisamy and Baskaran (2005) and Mansour *et al.* (1994) that is line load divided by the maximum load. This index points out the optimal location when it obtains the biggest value. In the study (Perez *et al.*, 2000), a sensitivity approach based on line loss has been proposed for placement of series capacitors. Gerbex *et al.* (2001) have provided an idea regarding the optimal locations of FACTS devices without considering the investment cost of FACTS device and their impact on the generation cost. However, the optimal location considering the generation cost of the power plants and the investment cost of the device has been discussed by Cai and Erlich (2003). Optimal location problem by power loss reduction has been discussed in Yang *et al.* (1998). Lie and Deng (1997) were of the view that optimal locations of FACTS devices can be obtained by solving the economic dispatch problem plus the cost of these devices making the assumption that all lines initially have these devices.

The main objective of this study is to develop an approach to find and choose the optimal location of FACTS device (i.e., UPFC) based on the sensitivity of the total system active power loss with respect to the control variables of the UPFC in Nigerian grid system.

A brief scheme of Nigerian grid system: The increasing demand of electricity in this country has consequently led to building various power stations in different locations within the country. The power generated would have to be transmitted to different load centres in the country

through the national grid. The bulk of electric energy is transferred either by the 330 kV transmission lines or 132 kV transmission lines across the country. But the description and analysis of the Nigerian grid system will be limited to the 330 kV transmission lines in this study. The 330 kV lines are constructed to have double circuits though on separate towers for reliability and more power transmission capacity. It is only the extension of the 330 kV Shiroro substation to Abuja that has a single tower with double circuits. Basically, the means of generating electric energy in Nigeria is principally through thermal and hydro sources. The generating stations installed capacities are as shown in Table 1 (PHCN, 2004). It is observed that the thermal power stations take a greater proportion in power output of Nigerian power system i.e.,

67.5% of the total power output. Among the thermal power stations, Egbin thermal power station gives the highest power output. The choice of location of some of these generation stations was obviously due to the existence of a natural falls at their various locations like Kainji, Jebba and Shiroro while the development of other generation stations was determined by the demand and the availability of energy source (natural gas). These were the factors that gave rise to the location of the first gas turbines at Afam and Delta. With the developments of all these generation stations, all the electricity produced are pooled together and transmitted to various load centres within the country. Figure 1 showed the Nigerian network modeled as 31 buses and 33 branches fed by 3 hydro units and 4 thermal units.

Table 1: The Electricity power stations of Power Holding Company of Nigeria (PHCN)

Power stations	Year commissioned	Type/fuel used	Installed capacity (MW)	No. of turbines	Percent in national grid	Available capacity as at 30/12/2003 (MW)
Kainji	1968	Hydro	760.0	8	12	410
Jebba	1986	Hydro	578.0	6	9	540
Shiroro	1990	Hydro	600.0	4	10	600
Egbin	1985	Thermal steam/NG, HPFO	1320.0	6	22	1170
Sapele	1978	Thermal steam/HPFO,	720.0	10	17	170
	1981	NG Thermal gas/HPFO, NG	300.0	-	-	-
Ijora	1978	Thermal gas turbine/Na	60.0	3	1	15
Delta	1966	Thermal gas turbine/Na	942.0	20	13	5288
Afam	1965	Thermal gas turbine/Na	986.6	17	16	325
Total of installed generative capacity			6136.0	-	-	-

PHCN (formerly called, NEPA) NEWS bulletin (2004) PHCN (2004)

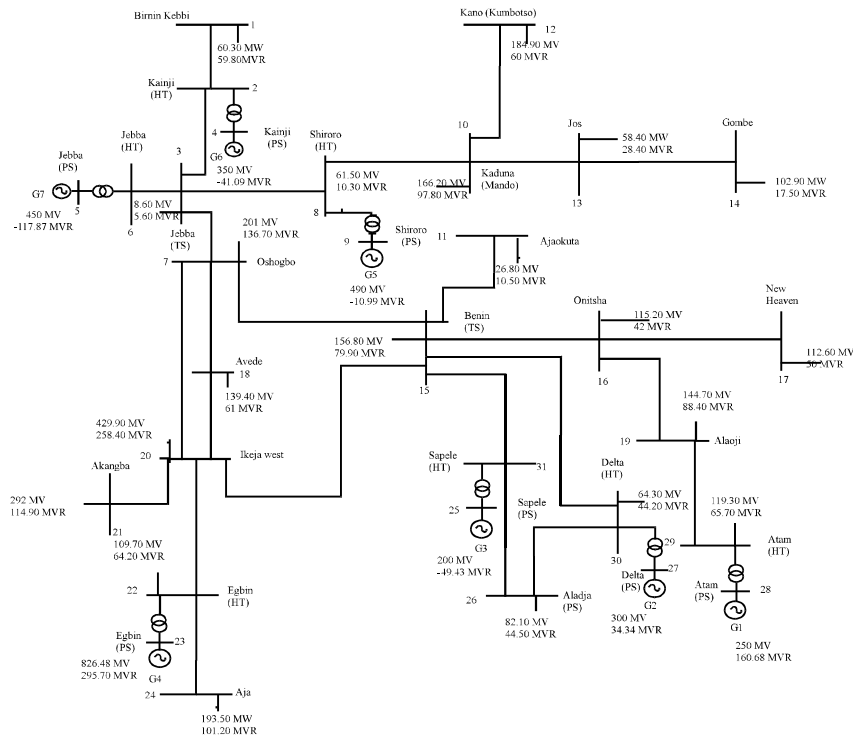


Fig. 1: The network of 330 kv Nigerian grid system

Mathematical model of the UPFC: Figure 2 shows a one line circuit diagram for UPFC consisting of a shunt Voltage Sourced Converter (VSC 1) and a series Voltage Sourced Converter (VSC 2) whose DC capacitors are coupled, thus allowing active power to circulate between the two voltage sourced converters. Since the net active generation by the two coupled voltage sourced converters is zero with negligible power losses, the loadflow equations could be shown by Chow (2004):

$$V_s = V_d \tag{1}$$

$$\frac{V_g (V_{pq} \sin(\theta_{pq} - \varphi_2) - V_s \sin(\theta_{pq} - \theta_s))}{X_{t2}} = P_d \tag{2}$$

$$\frac{-V_g (V_g - V_s \cos(\theta_{pq} - \theta_s) + V_{pq} \cos(\theta_{pq} - \varphi_2))}{X_{t2}} = Q_d \tag{3}$$

$$P_1 + P_2 = 0 \tag{4}$$

Where P_d and Q_d are the desired active and reactive power, respectively flowing into Bus g and V_d is the desired voltage at Bus s . A simplified control system block diagram (Huang *et al.*, 1997) of the UPFC is shown in Fig. 3. V_{dc} is the constant dc voltage which controls the firing angle φ_1 of VSC 1. V_s is the constant sending end ac voltage that controls m_1 of Pulse Width Modulation controller of VSC 1. Actually, m_1 and m_2 are the PWM control effects in obtaining desired converter voltages. V_p and V_q obtained from the constant line P and Q control are the control of m_2 and φ_2 of VSC 2 to realize constant power flow or constant series compensation control. Thus, m_1 , m_2 , φ_1 and φ_2 are obtained according to the UPFC control model.

Mathematical formulation based on sensitivity analysis:

Since the installation of most of the FACTS devices requires high capital cost then exhaustive calculations should be done in siting or locating the FACTS devices to damp inter-area oscillations, minimize transmission line loss as well as the overall cost function and enhance the voltage stability. Sensitivity analysis is the main focus to achieve this purpose as it concerns minimization of total active power losses in power system network.

The sensitivity analysis, if applied in more general sense could contribute to find appropriate location and action of the UPFC. Actually, the sensitivity analysis can suitably be explained and implemented when UPFC is inserted (embedded) in a transmission line. Sensitivity analysis of total active power losses is taken to show critical points of power system during time domain voltage collapse scenario with all three UPFC's parameters controlled simultaneously. Often, sensitivity involves the inverse of extended Jacobi matrix and therefore has larger magnitudes as the critical point is being approached with abrupt change to opposite sign as it is crossed (Wang, 1999). The appearance of the critical point represents a reliable sign of impending voltage unstable situation that could trigger voltage support from the UPFC. Therefore, if the sensitivity analysis is applied with respect to the set of the UPFC's control parameters it is possible to define its adequate regulating action. If the differential algebraic equations of power system is shown thus:

$$\dot{x} = f(x, y, p) \tag{5}$$

$$0 = g(x, y, p)$$

which could be linearised around an operating point to result in:

$$\Delta \dot{x} = f_x \Delta x + f_y \Delta y + f_p \Delta p \tag{6}$$

$$0 = g_x \Delta x + g_y \Delta y + g_p \Delta p$$

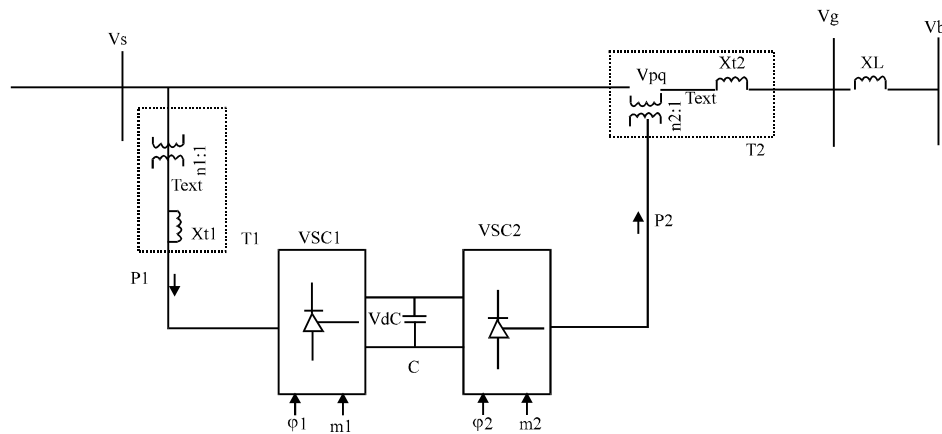


Fig. 2: Transmission line with UPFC installed

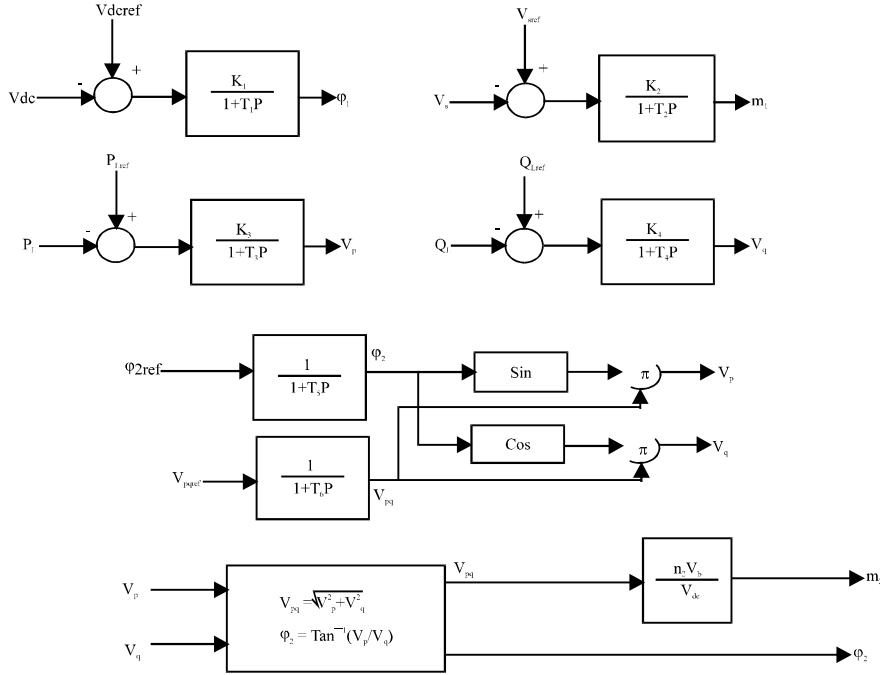


Fig. 3: UPFC control system block diagram

Where:

- Δx = The vector of the state variables
- Δy = Corresponds to the vector of real and reactive load powers
- Δp = Represents the vector of arbitrary parameters which may include the UPFC's set of control parameters (r, γ, Q_{convl})
- r = The magnitude of the injected series voltage
- γ = The angle of the injected series voltage
- Q_{convl} = The shunt reactive power (Dizdarevic *et al.*, 1998)

By eliminating the vector of algebraic variables, the system state matrix is obtained:

$$\frac{dx}{dt} = A_s \times \Delta x; A_s = [f_p - f_y g_y^{-1} g_x] \quad (7)$$

Therefore, the network equations for non-generating buses incidental with the UPFC shunt i and series j buses are shown as follows:

$$P_i(\theta, V) = \sum_{m=1}^n (G_{im} V_i V_m \cos \theta_{im} + B_{im} V_i V_m \sin \theta_{im}) - r b_s V_i V_j \sin(\theta_{ij} + \gamma) \quad (8)$$

$$Q_i(\theta, V) = \sum_{m=1}^n (G_{im} V_i V_m \sin \theta_{im} - B_{im} V_i V_m \cos \theta_{im}) - r b_s V_i^2 \cos \gamma + Q_{convl} \quad (9)$$

$$P_j(\theta, V) = \sum_{m=1}^n (G_{jm} V_j V_m \cos \theta_{jm} + B_{jm} V_j V_m \sin \theta_{jm}) - r b_s V_i V_j \sin(\theta_{ij} + \gamma) \quad (10)$$

$$Q_j(\theta, V) = \sum_{m=1}^n (G_{jm} V_j V_m \sin \theta_{jm} - B_{jm} V_j V_m \cos \theta_{jm}) - r b_s V_i V_j \cos(\theta_{ij} + \gamma) \quad (11)$$

In Eq. 10, the term Q_{convl} which is equal to $I_{convlq} V_i S_{convl}/S_B$ enables variable I_{convlq} to be set as parameter. This formulation of the model makes the computation of the sensitivities easy to be implemented in straight forward manner.

Sensitivity analysis of total active power loss: The total active power loss is formulated as follows (Dizdarevic *et al.*, 1998) :

$$P_{loss}(\theta, V) = \sum_{m=1}^n V_m \sum_{k=1}^n V_k G_{mk} \cos \theta_{mk} \quad (12)$$

Since the loss minimization is of concern, the sensitivity is to be computed. Change in the loss ΔP_{loss} is expressed as:

$$\Delta P_{loss}(x, y, p) = \frac{\partial P_{loss}^s}{\partial x} \Delta x + \frac{\partial P_{loss}^s}{\partial y} \Delta y + \frac{\partial P_{loss}^s}{\partial p} \Delta p \quad (13)$$

From Eq. 6, changes Δx and Δy with respect to Δp are:

$$\begin{aligned} \Delta x &= A_s^{-1} (f_y g_y^{-1} g_p - f_p) \Delta p \\ \Delta y &= -g_y^{-1} [g_x A_s^{-1} (f_y g_y^{-1} g_p - f_p) + g_p] \Delta p \end{aligned} \quad (14)$$

Since the partial derivatives are as follows:

$$\frac{\partial P_{loss}}{\partial x} = 0; \frac{\partial P_{loss}}{\partial p} = 0$$

and

$$\frac{\partial P_{loss}}{\partial y} = \left\{ \begin{aligned} \frac{\partial P_{loss}}{\partial \theta_m} &= -2 \sum_{\substack{k=1 \\ k \neq m}}^n V_m V_k G_{mk} \sin \theta_{mk} \\ \frac{\partial P_{loss}}{\partial V_m} &= 2 \sum_{k=1}^n V_k G_{mk} \cos \theta_{mk} \end{aligned} \right\} \quad (15)$$

then the sensitivity $[dp_{loss}/dp]$ is finally expressed as:

$$\frac{dP_{loss}^c}{dP} = -\frac{\partial P_{loss}^c}{\partial y} g_y^{-1} [g_x A_s^{-1} (f_y g_y^{-1} g_p - f_p) + g_p] \quad (16)$$

In this formulation $f_p = 0$ enabling some more simplification, where g_p is a three column matrix ($g_r, g_y, g_{i_{conv1q}}$) simply obtained by differentiating network Eq. 8-11 with respect to the UPFC's set of control parameters (r, γ, I_{conv1q}).

Reduction of total system active power loss: Here, we look at a method based on the sensitivity of the total system active power loss (P_L) with respect to the control variables of the FACTS device. For UPFC placed between buses i and j , the considered control parameter is the injected series voltage, V_{ij} of controllable magnitude and its phase angle. The active power loss sensitivity factor with respect to these control variables may be given as: loss sensitivity with respect to control parameter V_{ij} of UPFC placed between buses i and j :

$$a_{ij} = \frac{\partial P_L}{\partial V_{ij}} \quad (17)$$

and this can be deduced from Eq. 17 as:

$$\frac{\partial P_L}{\partial V_{ij}} = 2 V_i V_j \cos(\delta_i - \delta_j) + 2 V_i V_j \sin(\delta_i - \delta_j) \quad (18)$$

Selection of optimal site of unified power flow controller: Using the loss sensitivity as computed before, the criteria for deciding the device location are in obtaining the highest value of loss sensitivity index, a_{ij} . Therefore in order to determine the optimal

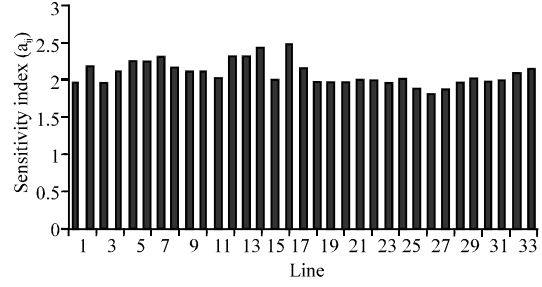


Fig. 4: Real power loss sensitivity index

Table 2: Real power loss sensitivity index for UPFC

Line	From bus (i)	To bus (j)	Sensitivity index (a _{ij})
1	1	2	1.9455
2	2	3	2.1788
3	2	4	1.9473
4	3	6	2.1152
5	3	7	2.2570
6	3	8	2.2298
7	5	6	2.2906
8	7	15	2.1641
9	7	18	2.0941
10	7	20	2.1159
11	8	9	2.0092
12	8	10	2.3171
13	10	12	2.3110
14	10	13	2.4144
15	11	15	1.9772
16	13	14	2.4712
17	15	16	2.1608
18	15	20	1.9504
19	15	30	1.9289
20	15	31	1.9560
21	16	17	1.9812
22	16	19	2.0013
23	18	20	1.9509
24	19	29	2.0153
25	20	21	1.8810
26	20	22	1.8074
27	22	23	1.8558
28	22	24	1.9342
29	25	31	2.0217
30	26	30	1.9644
31	26	31	1.9909
32	27	30	2.0703
33	28	29	2.1464

placement of the UPFC device in Nigerian grid system (Fig. 4), the active power loss sensitivity analysis should be performed. The sensitivity index a_{ij} is computed for each line in the system and the numerical results of siting the UPFC are shown in Table 2. The line having the highest loss sensitivity index is chosen for placement of the UPFC device. It is obvious that line 16 from Fig. 4 has the highest value of loss sensitivity index and therefore, should be considered more appropriate for location of UPFC device than other lines and of course, the location of the UPFC should be such as to minimize the system real power losses. The system configuration for the case study is shown in Fig. 5.

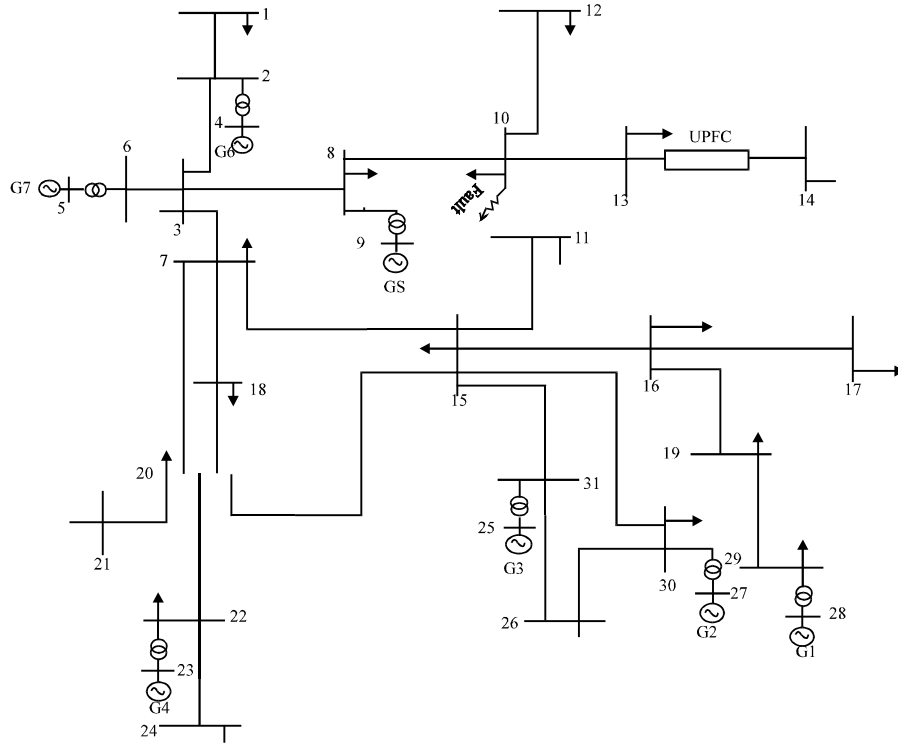


Fig. 5: 7-machine 31-bus test system network for case study

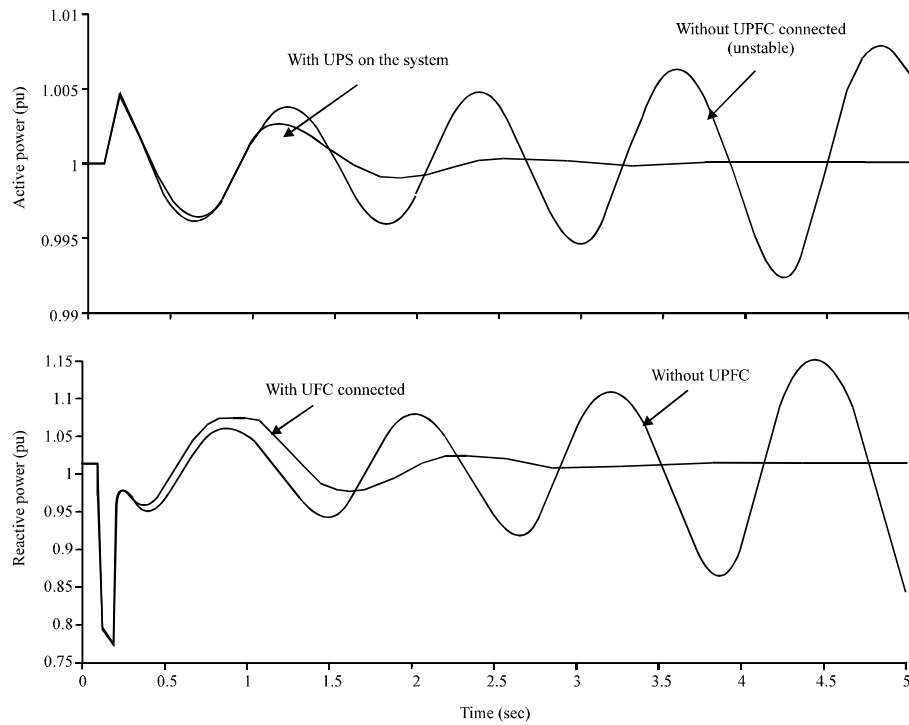


Fig. 6: Active and reactive power flow with and without UPFC

Performance evaluation of the system with UPFC: Sensitivity analysis is applied with respect to the control

variables of the unified power flow controller. It is however, introduced to determine the indices of each of

the line for the optimal siting of the UPFC aimed at enhancing voltage stability of Nigerian grid network. Subsequently, line 16 was found the best location for the UPFC as it has the largest value of sensitivity index. As the UPFC is located on the power system network, a voltage collapse scenario is established in order to analyze the effect of UPFC in solving the voltage unstable situation. The system voltage becomes unstable after a three-phase short circuit is applied at bus 10 at the generators' rated power level in Fig. 5, which is cleared after 100 ms by permanent line outage. In order to avoid the collapse, the voltage support and a coordinated control strategy are applied at the UPFC. The system responses are simulated using Power System Analysis Toolbox (PSAT) in MATLAB environment. Figure 6 shows the system responses with and without UPFC. It can be observed from Fig. 6 that the UPFC with coordinated controller can greatly improve the damping of the system and enhance voltage stability margin.

CONCLUSION

Sensitivity analysis is described in this research to optimally locate UPFC in the Nigerian grid system. The sensitivity of the total system active power loss is computed with respect to the control variables of the UPFC. This sensitivity index has been termed as the active power loss sensitivity factor whose maximum value on the overall transmission lines determines the optimal placement of the UPFC. Finally, the effectiveness of the proposed approach of the UPFC siting has been validated on a practical 7-machine 31-bus Nigerian grid network with respect to enhancing the static and dynamic voltage stability margins and hence active power loss reduction.

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