

Investigating the Capability of Power Flow Regulation by Unified Power Flow Controller (UPFC) in a Single-Machine-Infinite Bus System

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Abstract

The capability of regulating power flow in Nigerian Grid System using UPFC is the main focus in this paper. Consequently, three control methods, namely, voltage control through shunt compensation, real power flow control through quadrature voltage injection and reactive power flow control through in-phase voltage injection for the UPFC were examined in order to improve the transient stability of the power system. The quadrature voltage control was found to be effective in reducing the transient swings whereas in-phase voltage control was effective in improving the transient stability margin. Finally, the overall performance of the UPFC was evaluated in a single-machine infinite bus system by nonlinear simulations, and results obtained showed the effectiveness of the controller in improving the dynamic stability of the system and provide better damping to electromechanical oscillations.

Keywords

UPFC; FACTS devices; Single-Machine-Infinite Bus; Power System; Transient Stability

Introduction

Unified Power Flow Controller (UPFC) is one of the FACTS devices, which can control power system parameters such as terminal voltage, line impedance and phase angle. Therefore, it can be used not only for power flow control, but also for power system stabilizing control [1]. Unified Power Flow Controllers are capable of directing real and reactive power flows through a designated route and regulating the system voltage through reactive power compensation. Thus, UPFC provides several features for power flow control namely: voltage control through shunt compensation, real power flow control through quadrature voltage injection and reactive power flow control through in-phase voltage injection [2]. Hence, the capability of transmission facilities can be better utilized. The mechanism of these three control methods of UPFC in improving the transient stability of the power system will be examined.

However, some works have been done on various control methods for the UPFC and documented in literature by some authors. Smith and et al. [3] proposed decoupled control algorithms of the two components of UPFC series voltage which are quadrature and in-phase with the line current, by active and reactive power respectively. The decoupled control algorithms are based on approximate relationship. Ref. [4] also proposed that the shunt compensation of UPFC is controlled to maintain the system bus voltage. Furthermore, the authors asserted that the two components of UPFC can be controlled in coordination by Strip Eigenvalue Assignment method. Bialek, et al. [5] in their own view, presented an approach based on the use of the nonlinear system model and application of the direct Lyapunov method to improve damping of power swings using the unified power flow controller. They derived a state-variable control strategy using locally available signals of real and reactive power. Chang and Hsu [6] developed a systematic approach based on the root locus method and pole assignment to reach proper proportional-integral (PI) controller gains for the UPFC control system in order to improve system dynamics performance under disturbance conditions.

This paper, however, investigates the three control methods, namely, voltage control through shunt compensation, real power flow control through quadrature voltage injection and reactive power flow control through in-phase voltage injection for the UPFC in order to

improve the stability of the power system, thus providing the security for the increased power flow.

Power System Model with UPFC

A simple power system is chosen and studied in PSCAD/EMTDC environment in order to evaluate the performance of the UPFC with different control strategies. The power system whose parameters are given in appendix comprises a 100MVA, 16.64kV synchronous generator connected to an infinite bus through a transmission line and a transformer stepping up the voltage to 330kV. The generator is assumed to have Automatic Voltage Regulator (AVR) controlling its terminal voltage. The single-machine infinite-bus (SMIB) system used in this study is for better understanding of transient stability of Nigerian Grid System since the purpose for the use of UPFC is to improve transient stability of the system. The UPFC is placed between bus 2 and bus 3 on the transmission line as shown in Figure 1. The UPFC is designed to control the power (real and reactive) through line as well as the voltage at bus 3 using PWM power controller.

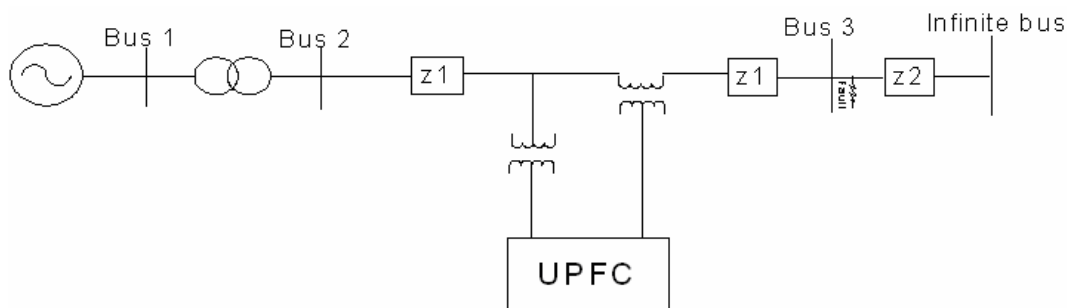


Figure 1. Single-machine infinite bus system with UPFC

Generator model

A detailed dynamic generator model for the single-machine infinite bus system is used for a UPFC controller design to give more accurate controller parameters. It is given as follows [7, 8]:

Mechanical equations:

$$\Delta \dot{\delta}(t) = \omega(t) \quad (1)$$

$$\dot{\omega}(t) = -\frac{D_m}{2H} \omega(t) + \frac{\omega_o}{2H} [P_m - P_e(t)] \quad (2)$$

$$\Delta P_e(t) = P_e(t) - P_m \quad (3)$$

where $\Delta\delta(t) = \delta(t) - \delta_o$; $\delta(t)$ is the power angle of the generator; δ_o is the power angle of the generator at the operating point; $\omega(t)$ is the relative speed of the generator; P_m is the mechanical input power (assumed constant); $P_e(t)$ is the real power delivered by the generator; $\omega_o = 2\pi f_o$ is the synchronous machine speed; D_m is the per unit damping constant; H is the inertia constant.

Generator electrical dynamics:

$$\dot{E}'_q(t) = \frac{1}{T'_{do}} [E_f(t) - E_q(t)] \quad (4)$$

where $\dot{E}'_q(t)$ is the transient Electromotive force (EMF) in the quadrature axis of the generator; $E_q(t)$ is the EMF in the quadrature axis; $E_f(t)$ is the equivalent EMF in the excitation coil; T'_{do} is the direct axis open-circuit transient time constant.

Electrical equations:

$$E_q(t) = \frac{x_{ds}}{x'_{ds}} E'_q(t) - \frac{x_d - x'_d}{x'_{ds}} V_E \cos \delta(t) \quad (5)$$

$$P_e(t) = \frac{V_E}{x_{ds}} E_q(t) \sin \delta(t) \quad (6)$$

$$I_q(t) = \frac{V_E}{x_{ds}} \sin \delta(t) = \frac{P_e(t)}{x_{ad} I_f(t)} \quad (7)$$

$$Q(t) = \frac{V_E}{x_{ds}} E_q(t) \cos \delta(t) - \frac{V_E^2}{x_{ds}} \quad (8)$$

$$E_q(t) = x_{ad} I_f(t) \quad (9)$$

$$x_{ds} = x_d + x_T + xL/4 + x_E \quad (10)$$

$$x'_{ds} = x'_d + x_T + xL/4 + x_E \quad (11)$$

where $E'_q(t)$ is the transient Electromotive force (EMF) in the quadrature axis of the generator; $E_q(t)$ is the EMF in the quadrature axis; $Q(t)$ is the reactive power; $I_f(t)$ is the excitation current; $I_q(t)$ is the quadrature axis current; x_{ad} is the mutual reactance between the excitation coil and the stator coil; x_d is the direct axis reactance of the generator; x'_d is the direct axis transient reactance of the generator; x'_{ds} is the mutual transient reactance between the direct axis of generator and transformer; $\delta(t)$ is the power angle of the generator; x_{ds} is the

mutual reactance between the direct axis of generator and transformer; x_T is the reactance of the step up transformer; x_E is the reactance of the Thevenin equivalent viewed from bus \bar{V}_1 ; V_E is the voltage magnitude of the Thevenin equivalent viewed from bus \bar{V}_1 .

UPFC model and control strategies

The mathematical UPFC model was derived with the aim of being able to study the relations between the electrical transmission system and UPFC in steady-state conditions. The basic scheme of this model is shown in Figure 2.

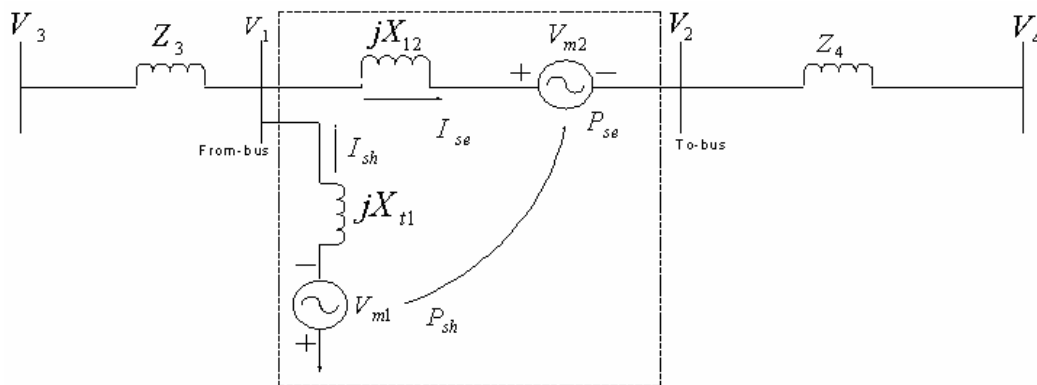


Figure 2. Model of UPFC

The mathematical UPFC model was derived with the aim of being able to study the relations between the electrical transmission system and UPFC in steady-state conditions. The basic scheme of this model is shown in Figure 2. 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 3, the power circulation and the line flow are calculated by the following expressions [9]:

$$P_{sh} + P_{se} = 0 \text{ (neglecting losses)} \quad (12)$$

$$P_L = V_2 (V_{m2} \sin(\theta_2 - \alpha_2) - V_1 \sin(\theta_2 - \theta_1)) / X_{t2} \quad (13)$$

$$Q_L = -V_2 (V_2 - V_1 \cos(\theta_2 - \theta_1) + V_{m2} \cos(\theta_2 - \alpha_2)) / X_{t2} \quad (14)$$

where P_{sh} is the power at the shunt side of the UPFC; P_{se} is the power at the series part of UPFC; P_L is the real power flow; Q_L is the reactive power flow; V_2 is the voltage at the bus2; V_{m2} is the series voltage of UPFC; V_1 is the voltage at bus1; X_{t2} is the reactance between buses 1 and 2; θ_1 and θ_2 are the angles of buses 1 and 2 respectively.

The vector diagram of the UPFC is as shown in Figure 3 [10].

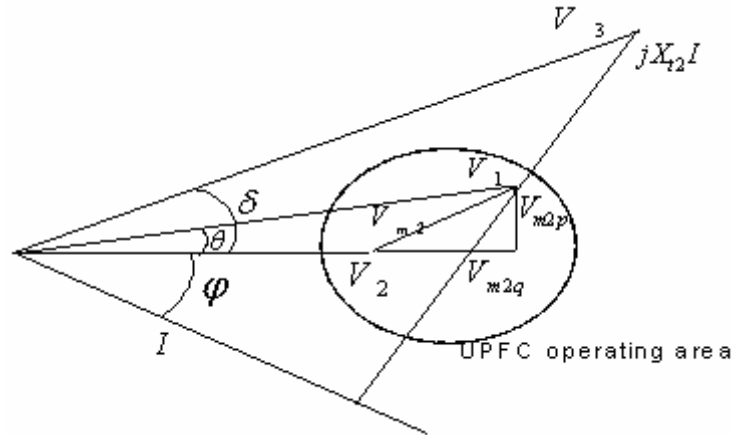


Figure 3. Vector diagram of a UPFC connected to a network

The vector diagram of an UPFC connected to a network (Figure 2) is presented in Figure 3. According to Figure 3, V_{m2p} and V_{m2q} are the components of the series voltage of UPFC. They are proportional to the voltage at the point of connection of UPFC and can be written as:

$$V_{m2p} = V_2\gamma(t) \text{ and } V_{m2q} = V_2\beta(t) \quad (15)$$

where $\beta(t)$ and $\gamma(t)$ are the control variables. The following equations are deduced from figure 3:

$$\begin{aligned} V_2 + V_{m2q} + X_{t2}I \sin \varphi &= V_3 \cos \delta \\ V_{m2p} + X_{t2}I \cos \varphi &= V_3 \sin \delta. \end{aligned} \quad (16)$$

Multiplying (16) by V_2 , (17) will be obtained:

$$\begin{aligned} P_2 &= \frac{V_2 V_3}{X_{t2}} \sin \delta - \frac{V_2 V_{m2p}}{X_{t2}} \\ Q_2 &= \frac{V_2 V_3}{X_{t2}} \cos \delta - \frac{V_2 V_{m2q}}{X_{t2}} - \frac{V_2^2}{X_{t2}} \end{aligned} \quad (17)$$

The partial derivatives of P_2 and Q_2 are calculated as (18) and (19) respectively:

$$\begin{aligned}\frac{dP_2}{dt} &= \frac{\partial P_2}{\partial \delta} \times \frac{d\delta}{dt} + \frac{\partial P_2}{\partial V_{m2p}} \times \frac{d(V_{m2p})}{dt} \\ \frac{dP_2}{dt} &= \frac{(-V_{m2p})V_3}{KX_{t2}} - \frac{V_2}{X_{t2}} \times \frac{d(V_{m2p})}{dt}\end{aligned}\quad (18)$$

$$\begin{aligned}\frac{dQ_2}{dt} &= \frac{\partial Q_2}{\partial \delta} \times \frac{d\delta}{dt} + \frac{\partial Q_2}{\partial V_{m2q}} \times \frac{d(V_{m2q})}{dt} \\ \frac{dQ_2}{dt} &= \frac{(-V_{m2q})V_3}{KX_{t2}} - \frac{V_2}{X_{t2}} \times \frac{d(V_{m2q})}{dt}\end{aligned}\quad (19)$$

Therefore, modulation controller for series-injected voltage can be designed by using (18) and (19). The value of K is chosen so that the injected series voltage remains at its nominal value. The values of V_2 and V_3 can be chosen as 1.0 per unit (p.u.). The injected series voltage, V_{m2} is calculated as:

$$V_{m2} = \sqrt{V_{m2p}^2 + V_{m2q}^2} \quad \text{and} \quad \delta = \text{Arctg}\left(\frac{V_{m2p}}{V_{m2q}}\right)\quad (20)$$

UPFC can be controlled in a variety of ways to meet different objectives. Basically, UPFC has two different control strategies, namely, (1) series compensator consisting of series inverter and series transformer modeled as a fully controllable voltage source which controls the real and reactive power flow through the transmission line. (2) Shunt compensator comprising shunt inverter, shunt transformer and connection filter modeled as a fully controllable voltage source with connection impedance including the leakage of the shunt transformer [11].

The series inverter provides the main function of the UPFC by injecting a voltage with magnitude V_{m2} , which is controllable and a phase angle δ in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in a reactive and active power exchange between itself and the ac system. The inverter generates the reactive power exchanged at the ac terminal internally [12]. The active power exchanged at the ac terminal is converted into dc power, which appears at the dc link as a positive or negative real power.

The basic function of shunt inverter is to generate or absorb the real power demanded by series inverter at the common dc link. The power demand by the series inverter at the dc link is converted back to ac by the shunt inverter and fed to the transmission line bus via a shunt-connected transformer. In addition to this the shunt inverter can also generate or absorb controllable reactive power if desired and thereby provides independent shunt reactive compensation for the line [13].

Simulations

To test the effectiveness of the UPFC controller, a balanced three-phase fault is applied to the line at the end close to bus 3 (see Figure 1) at 5.0s when the generator is operating at its rated power level. The duration of the fault is 0.10s. The system responses are simulated using PSCAD/EMTDC [14]. Figures 4 to 12 show the system responses with and without UPFC. It can be observed from these figures that the UPFC with coordinated controller can greatly improve the damping of the system and its stability.

The equations used in the simulation were from 1 to 11 and 13 & 14.

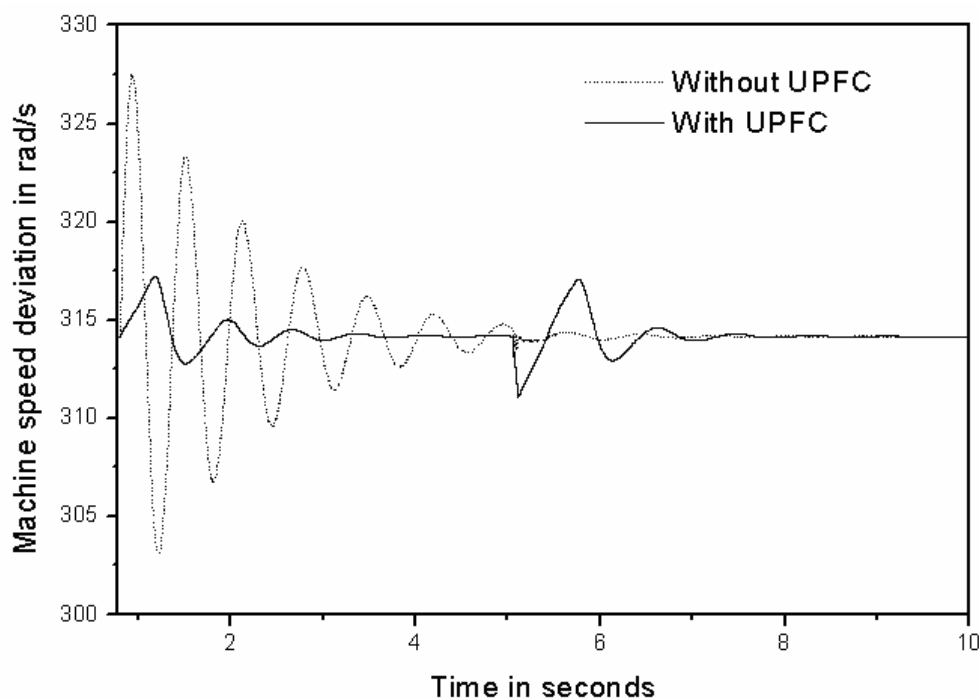


Figure 4. Speed response of the synchronous generator operating for a three-phase short circuit at end close to bus 3

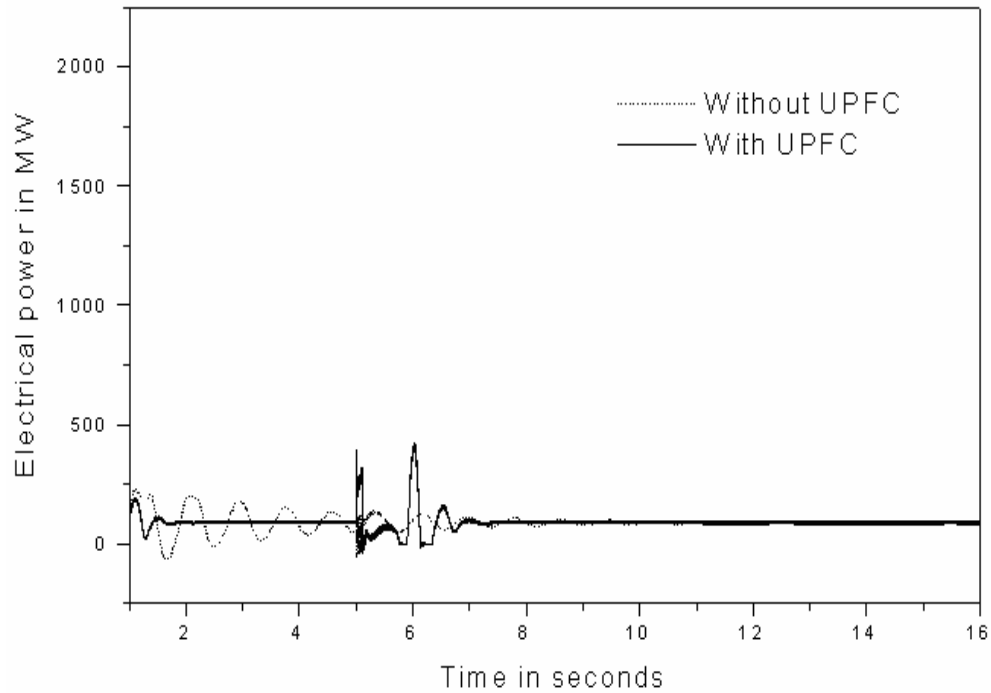


Figure 5. Electrical power output response of the synchronous generator operating for a three-phase short circuit at end close to bus 3

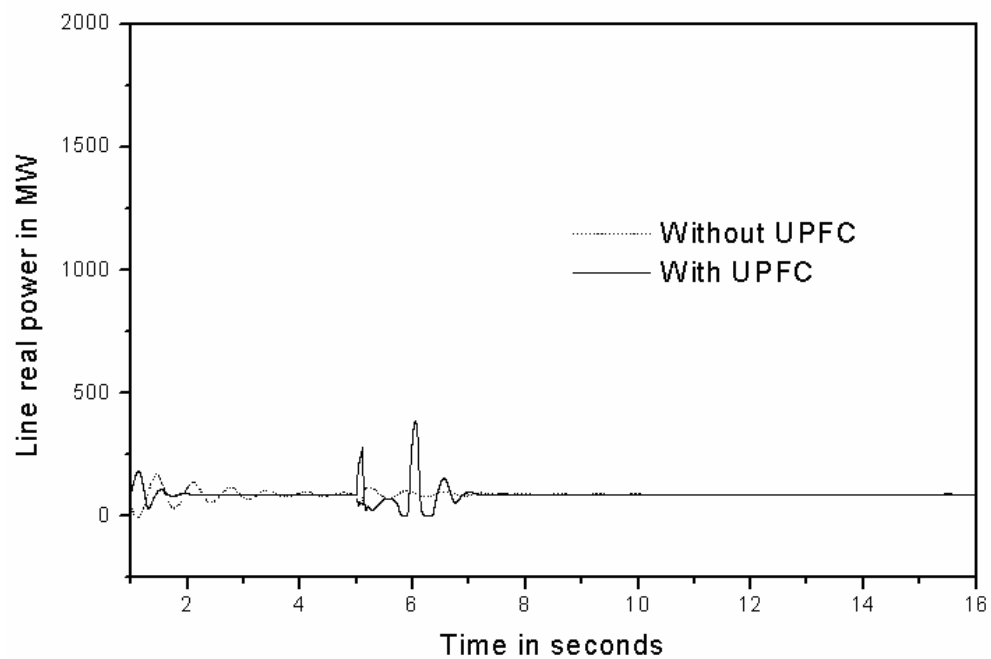


Figure 6. Transient corresponding to line real power

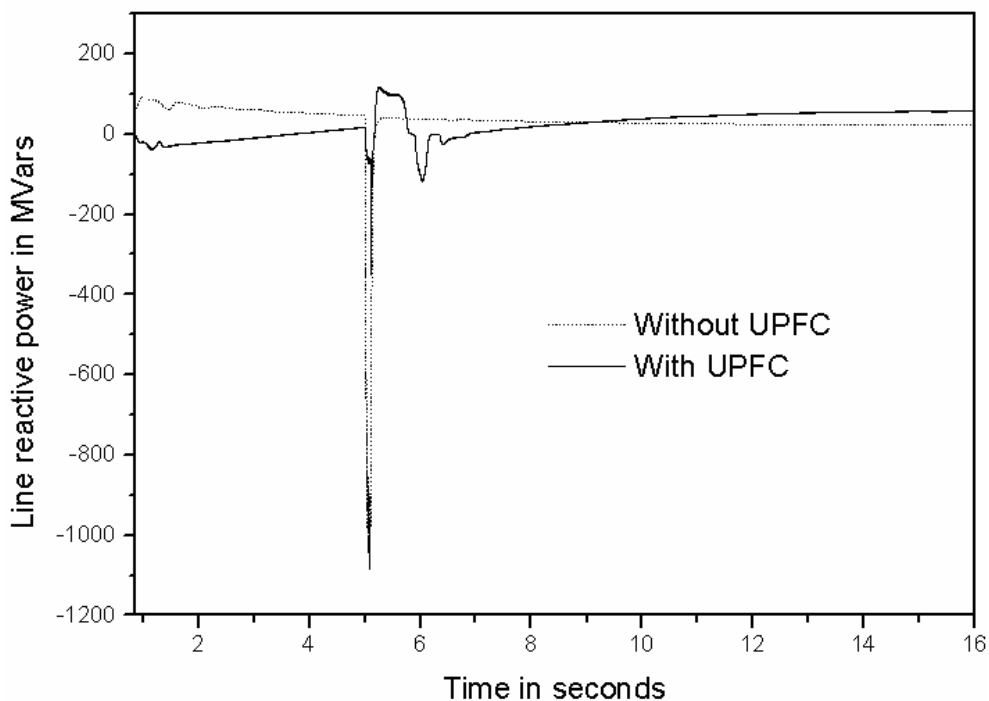


Figure 7. Transient corresponding to line reactive power.

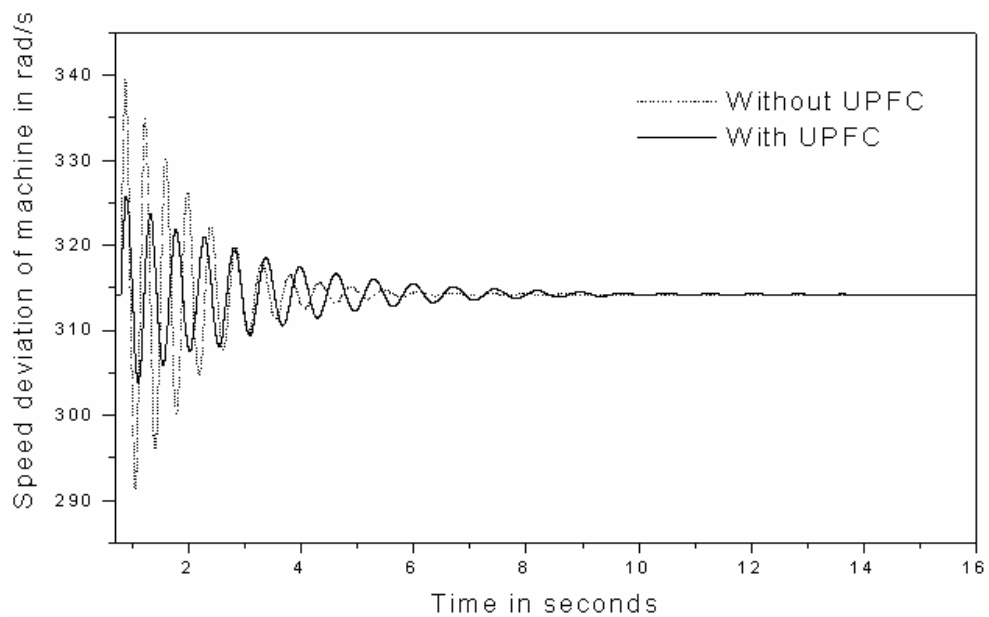


Figure 8. Speed response of the synchronous generator by quadrature voltage control

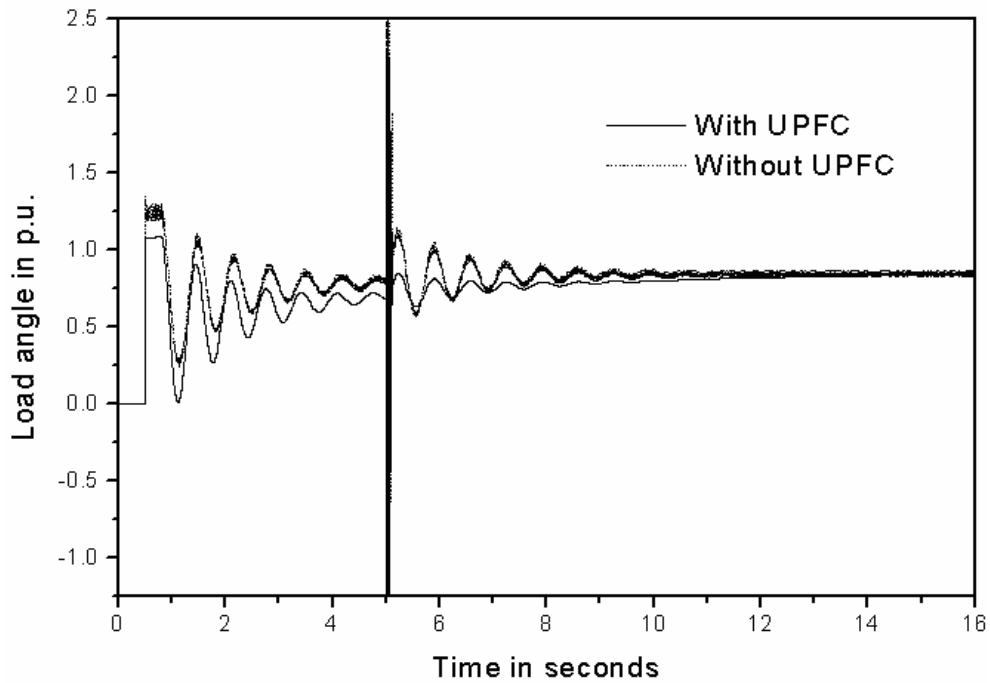


Figure 9. Load angle response of the synchronous generator at quadrature voltage control

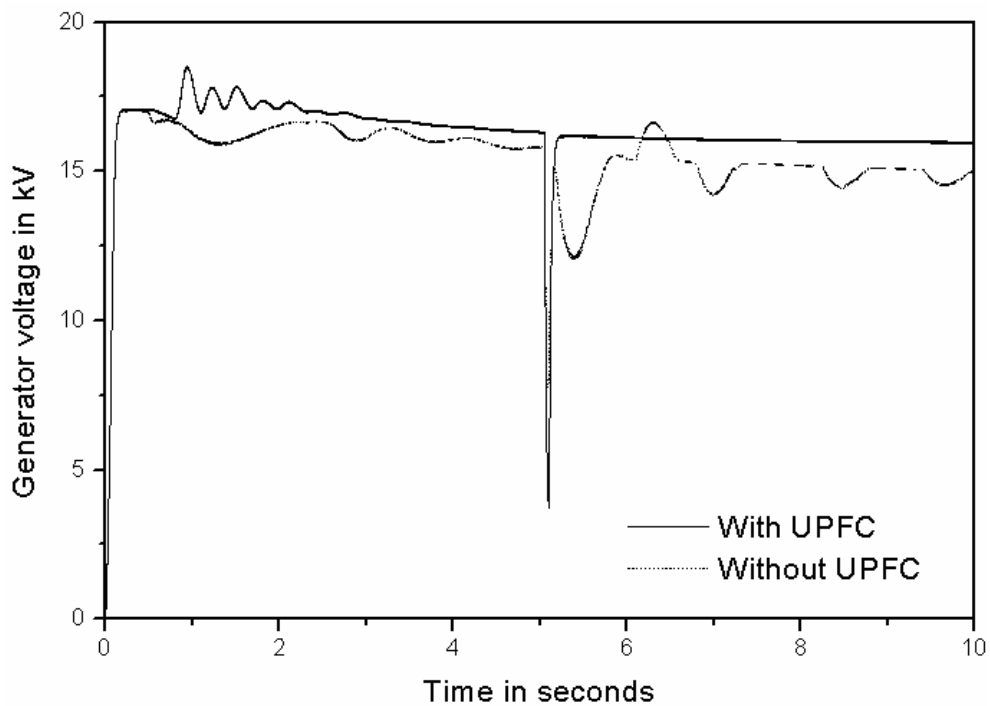


Figure 10. Terminal voltage response of the synchronous generator by quadrature voltage control

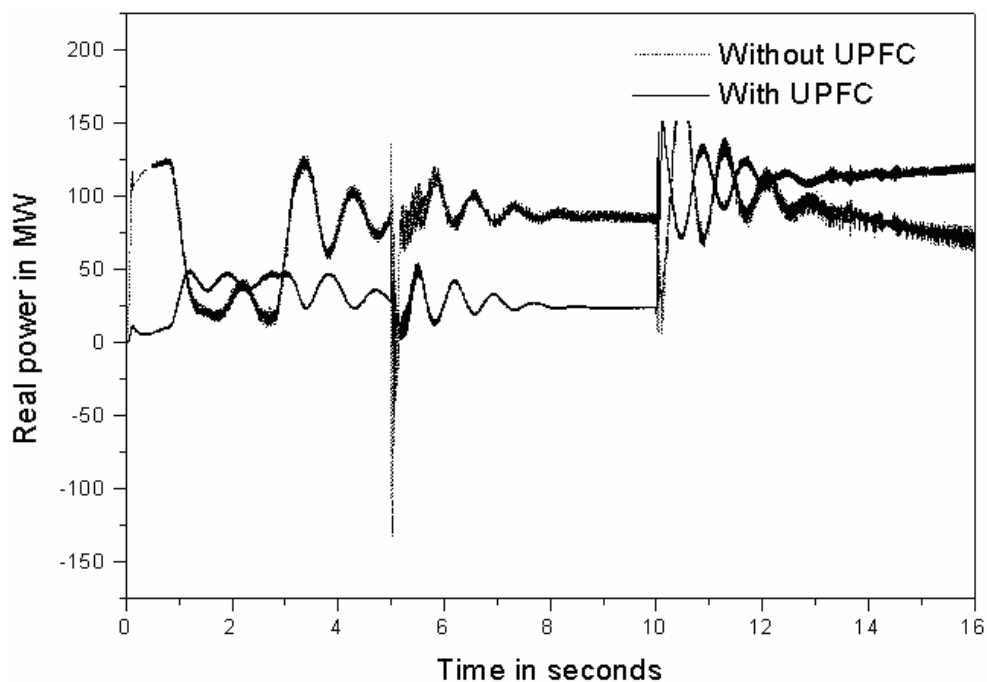


Figure 11. Transient corresponding to line real power by quadrature voltage control

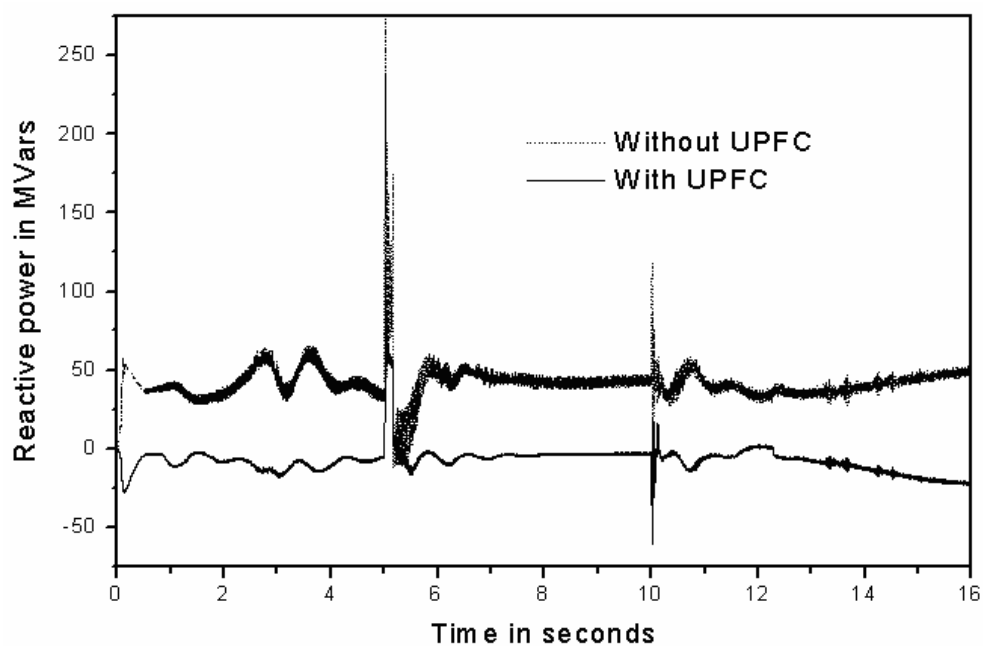


Figure 12. Transient corresponding to line reactive power by quadrature voltage control

Findings and Discussion

Under Shunt Compensation

The simulation results of shunt compensation are shown in Figure 4 to Figure 7.

It is observed that the dynamic oscillations in Figure 4 are well damped when UPFC is connected to the system, although they have large first swing after the fault is cleared.

From Figures 6 and 7, it can be seen that the real and reactive power could be controlled to a specific value after the fault is cleared, which shows that the UPFC is very effective in line flow control.

This, of course, limits the electrical power output of the generator (see Figure 5) which makes the rotor angle increase more than that when there is no UPFC.

Under Series Compensation

The two components of series compensation control are considered with respect to the injected voltage. These components are in-phase voltage and quadrature voltage.

The simulation results of the quadrature voltage control are as shown in Figures 8 to 12. It is observed that the transient swings are reduced, but it is poor in load flow control and damping control.

However, from the equal area criterion, it can be predicted that after the rotor angle reaches the maximum value in the first swing, this control strategy should be changed and should be aiming at damping of the subsequent swings.

But, with in-phase voltage control, the transient stability margin is significantly improved (see Figure 13).

It is noteworthy that the in-phase component contributes to the real power exchange between the series and shunt branch of the UPFC, and reduces the fluctuation in capacitor voltage at its zero value.

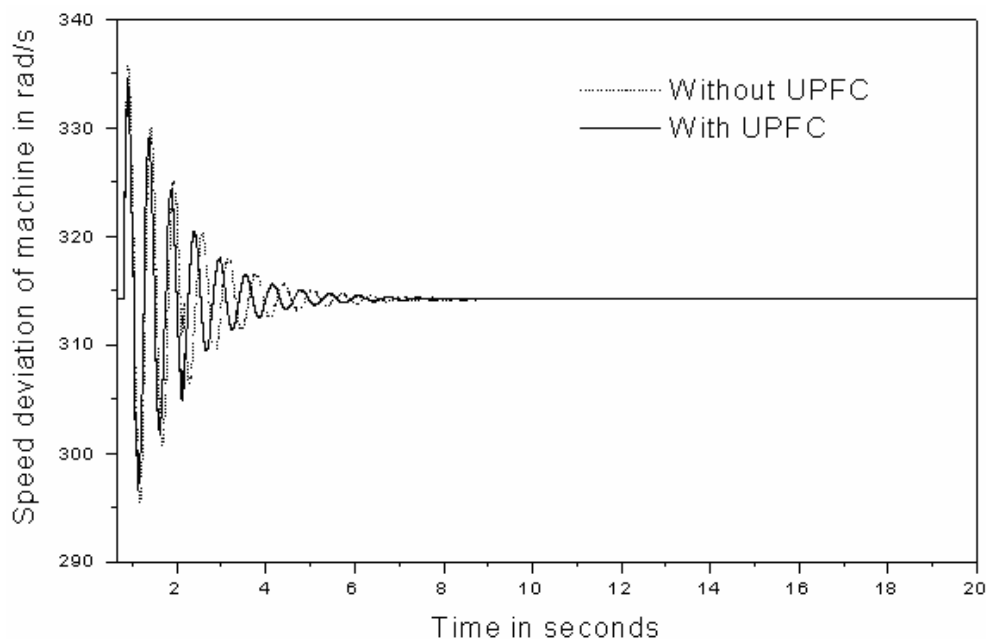


Figure 13: Improved transient stability margin by in-phase voltage control.

Conclusion

In this paper, the capability of regulating power flow in a Single-machine Infinite bus system as it affects Nigerian Grid System using UPFC has been investigated. The mechanism of the three control methods, viz, in-phase voltage control, quadrature voltage control and shunt compensation was also examined in improving the transient stability of the power system and these three control methods were separately considered in this work. The quadrature voltage control was found to be effective in reducing the transient swings whereas in-phase voltage control was effective in improving the transient stability margin. The performance of the UPFC model and its controller has been evaluated in a single-machine infinite bus system by nonlinear simulations. The results show that the controller significantly improves the dynamic stability of the system and provides better damping to electromechanical oscillations.

Appendix

The Power System used in this work comprises a synchronous generator whose parameters given in Table 1 were determined from [7]. The ratings of the generator are:

Rated Power = 100 MVA; Rated Voltage = 16.64 kV; Rated Current = 3.47 kA; Inertia constant, H = 3.12 s; Frequency = 50 Hz.

Table 1. Generator Parameters

$R_a = 0.0049$ per unit (p.u)	$X_d'' = 0.280$ p.u
$X_p = 0.163$ p.u	$T_{d0}'' = 0.039$ sec
$X_d = 1.014$ p.u	$X_q = 0.770$ p.u
$X_d' = 0.314$ p.u	$X_q' = 0.375$ p.u
$T_{d0}' = 6.550$ sec	$T_{q0}'' = 0.071$ sec

For transformer: MVA rating = 1000 MVA; Base operation frequency = 50 Hz; Primary/Secondary transformer ratings = 16kV/330kV; Positive sequence leakage reactance = 0.01932 per unit (p.u).

The parameters of UPFC PI controllers that are obtained by time response analysis and are given below. UPFC ratings:

For shunt branch	For series branch	
$Q_p = 0.1$	$U_d = 0.1$	$U_q = 0.1$
$K_{dc} = 1.0$	$K_d = 0.01$	$K_q = 0.01$

Shunt Transformer ratings = 330 kV/ 20kV; Rated power = 300MVA; Series Transformer ratings = 20kV/ 33kV; Rated power = 100MVA; $V_{dc} = 20kV$; $C = 2000\mu F$

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