EFFECT OF THE UPFC ON A MULTIMACHINE POWER SYSTEM STEADY STATE AND DYNMANIC PERFORMANCE

DJILANI KOBIBI Youcef Islam, HADJERI Samir, DJEHAF Mohammed Abdeldjalil
Intelligent Control and Electrical Power System Laboratory, Djillali Liabes University of Sidi Bel-Abbes, Algeria.
youcef_kobibi@univ-sba.dz, shadjeri@univ-sba.dz, med_djehaf@univ-sba.dz

Abstract: *The fast progress in power electronics is rapidly expanding the field of applications for the Flexible AC Transmission Systems (FACTS) controllers in power systems. FACTS technology is a new solution to improve the reliability and provide more controllability and flexibility for the power system. Unified Power Flow Controller (UPFC) is the most versatile FACTS that can control independently and simultaneously all the parameters (line impedance, voltage magnitude and phase angle) of the line power flow. This paper present a comparative study of a two area 9 bus multimachine power system with and without the UPFC based on the improvement of the power flow, and the amelioration of the dynamic stability under fault conditions.*

Key words: *FACTS, UPFC, Load flow, Stability.*

1. Introduction

Modern power systems are complex networks comprising of transmission Lines interconnecting all the generator stations, transformers and all the loading points. Electricity demand continues to increase despite the difficulty of building new generating units and transmission lines due to economic reasons and growing public impact on environmental policy.[1][2] A review of the traditional power system practices and concepts is necessary for this situation. This is to achieve greater operating flexibility and also for better utilization of existing power systems. [3]

With increased power transfer, transient and dynamic stability is of increasing importance for secure operation of power systems. Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance, such as a fault on transmission facilities, sudden loss of generation, or loss of a large load[[1][4]

Major advances have been made in control technologies and high power semiconductor devices during the last two decades. As high voltage power electronics become less expensive and have wider-range of operation, flexible ac transmission systems (FACTS) controller become more popular. FACTS controllers can provide better solutions to many of the stability problems that occur due to sudden load changes or faults [3]

FACTS devices are increasingly used as cost effective measures to improve transmission capacity, oscillation damping and stability improvement. This allows increased utilization of existing network closer to its thermal loading capacity, and thus avoiding the need to construct new transmission lines. [4]

Unified power flow controller (UPFC), regarded as one of the most versatile ones in the FACTS device family [5], [6], has the capabilities of controlling power flow in the transmission line, improving the transient stability, mitigating system oscillation, and providing voltage support.[7]

Several approaches have been taken to the modeling and control of the UPFC. The most common approach is to model the UPFC as a power injection model for power flow studies [8]-[9]. In the case where UPFC dynamics are included, the most common approach to controlling the UPFC has been to use PI control [10]-[11].

This paper aims to analyze the steady state of a multimachine power system, and the dynamic response to a fault with and without the UPFC, using the injection model of the UPFC in a MATLAB program for load flow analysis, and the UPFC simulation model established in SIMULINK, for the analysis of the dynamic performance.

2. Unified Power Flow Controller

2.1 Principle of Operation

The UPFC consists of two static converters, with a common DC link, which, through two coupling transformer, are connected in series and parallel, respectively, to the AC system as shown in Figure 1.

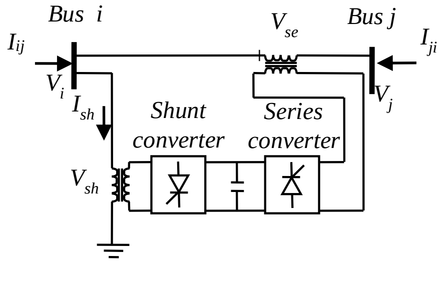
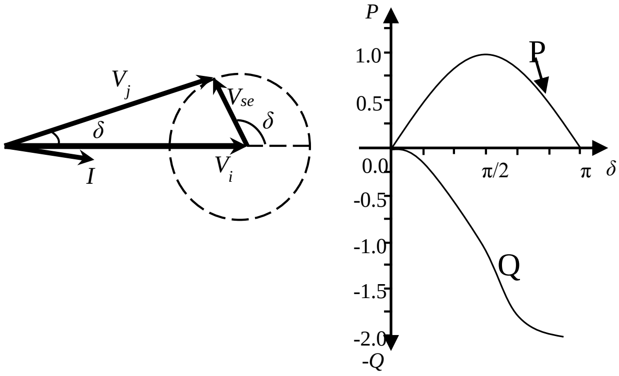


Fig.1. Single-line Diagram of a UPFC

The UPFC inject a voltage whose magnitude and phase angle vary according to the degree and type of compensation to be performed. Therefore, the phase shift between the voltage and current at its terminals determines the power exchange between the equipment and the AC system, as shown in Figure 2. [12]



(a) (b)

Fig.2. (a) Phasor Diagram of Voltages and Currents (b) Transmittable real power P and reactive power Q vs. transmission angle δ

2.2. UPFC Injection Model for Load flow studies

2.2.1. Mathematical model

A UPFC can be represented by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactance's of the two coupling transformers.

Figure 3 depicts two voltage-source model of UPFC. System voltage is taken as reference vector $V_i=V_i\angle 0°$ and $V_i'=V_{se}+V_i$.

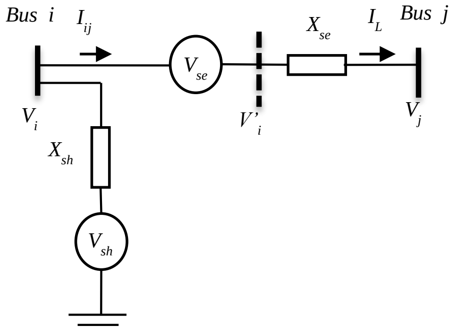


Fig.3.Voltage-source model of UPFC

Voltages sources V_{sh} and V_{se} are controllable in both their magnitudes and phase angles. r and γ are respectively the p.u. magnitude and phase angle of series voltage source, operating within the following specified limits given by:

$0\le r \le r_{max}$ and $-\pi \le \gamma \le \pi$ (1)

V_{se} should be defined as :

$$V_{se} = rV_ie^{j\gamma} \quad (2)$$

The model is developed by replacing voltage source V_{se} by a current source I_{se} parallel with the transmission line as shown in Figure 4, where $b_{se}=1/X_{se}$.

$$I_{se} = -b_{se}V_{se} \quad (3)$$

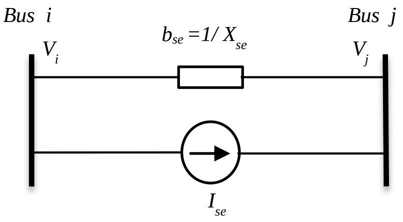


Fig.4. Replacement of series voltage source by current source

The current source I_{se} can be modeled by injection powers at the two auxiliary buses i and j.

$$S_{is} = V_i(-I_{se})^* \quad (4)$$

$$S_{js} = V_j(I_{se}) \quad (5)$$

Injected powers S_{is} and S_{js} can be simplified according to the following operations by substituting (2) and (3) into (4).

$$S_{is} = V_i(jb_{se}rV_ie^{j\gamma})^* \quad (6)$$

By using Euler Identity, ($e^{j\gamma}=\cos\gamma + j\sin\gamma$) (6) takes the form of:

$$S_{is} = V_i(e^{-(\gamma+90)}b_{se}rV_i^*) \quad (7)$$

$$S_{is} = V_i^2b_{se}r\left[\cos(-\gamma-90)+j\sin(-\gamma-90)\right] \quad (8)$$

By using trigonometric identities, (8) reduces to:

$$S_{is} = -rb_{se}V_i^2\sin\gamma - jrb_{se}V_i^2\cos\gamma \quad (9)$$

(9) can be decomposed into its real and imaginary components,

$$S_{is} = P_{is} + jQ_{is} \quad (10)$$

Where

$$P_{is} = -rb_{se}V_i^2\sin\gamma \quad (11)$$

$$Q_{is} = -rb_{se}V_i^2\cos\gamma \quad (12)$$

Similar modifications can be applied to (5); final equation takes the form of,

$$S_{js} = V_iV_jb_{se}r\sin(\theta_i-\theta_j+\gamma) + jV_iV_jb_{se}r\cos(\theta_i-\theta_j+\gamma) \quad (13)$$

(13) can also be decomposed into its real and imaginary parts,

$$S_{js} = P_{js} + jQ_{js} \quad (14)$$

Where

$$P_{js} = V_iV_jb_{se}r\sin(\theta_i-\theta_j+\gamma) \quad (15)$$

$$Q_{js} = V_iV_jb_{se}r\cos(\theta_i-\theta_j+\gamma) \quad (16)$$

Based on (11), (12), (15), and (16), power injection model of the series-connected voltage source can be seen as two dependent power injections at auxiliary buses i and j as shown in Figure 5. In UPFC, shunt branch is used mainly to provide both the real power P_{series}, which is injected to the system through the series branch, and the total losses within the UPFC. The total switching losses of the two converters is estimated to be about 2% of the power transferred for thyristor based PWM converters. [13]

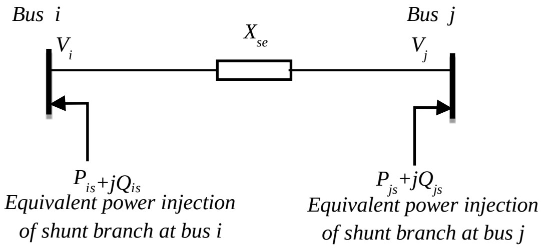


Fig. 5. Equivalent power injection of series branch

If the losses are to be included in the real power injection of the shunt-connected voltage source at bus *i*, P_{shunt} is equal to 1.02 times the injected series real power P_{series} through the series-connected voltage source to the system.

$$P_{shunt} = -1.02 P_{series} \tag{17}$$

The apparent power supplied by the series converter is calculated as:

$$S_{series} = V_{se} I_{ij}^{*} = re^{j\gamma} V_i \left(\frac{V_i' - V_j}{jX_{se}} \right) \tag{18}$$

Active and reactive power supplied by the series converter can be calculated from (20).

$$S_{series} = re^{j\gamma} V_i ((re^{j\gamma} V_i + V_i - V_j) / jX_{se})^{*} \tag{19}$$

$$S_{series} = \frac{rV_i e^{j(\theta_i+\gamma)} ((rV_i e^{-j(\theta_i+\gamma)} + V_i e^{-j\theta_i} - V_j e^{-j\theta_j})}{-jX_{se}} \tag{20}$$

$$S_{series} = jb_{se} r^2 V_i^2 + jb_{se} rV_i^2 e^{j\gamma} = jbV_iV_j e^{j(\theta_i - \theta_j + \gamma)} \tag{21}$$

$$\begin{aligned} S_{series} &= jb_{se} r^2 V_i^2 + jb_{se} rV_i^2 (\cos\gamma + j\sin\gamma) \\ &\quad - jb_{se} rV_iV_j (\cos(\theta_i - \theta_j + \gamma) \\ &\quad + j\sin(\theta_i - \theta_j + \gamma)) \end{aligned} \tag{22}$$

Final form (22) takes the form of

$$S_{series} = P_{series} + jQ_{series} \tag{23}$$

Where:

$$P_{series} = rb_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma) - rb_{se} V_i^2 \sin\gamma \tag{24}$$

$$\begin{aligned} Q_{series} &= -rb_{se} V_i V_j \cos(\theta_i - \theta_j + \gamma) \\ &\quad + rb_{se} V_i^2 \cos\gamma + r^2 b_{se} V_i^2 \end{aligned} \tag{25}$$

The reactive power delivered or absorbed by converter 1 is not considered in this model, but its effect can be modeled as a separate controllable shunt reactive source. In this case main function of reactive power is to maintain the voltage level at bus *i* within acceptable limits. In view of the above explanations, Q_{shunt} can be assumed to be 0. Consequently, UPFC mathematical model is constructed from the series-connected voltage source model with the addition of a power injection equivalent to $P_{shunt} + j0$ to bus *i*, as depicted in Figure 6.

$$\begin{aligned} P_{i,UPFC} &= 0.02 rb_{se} V_i^2 \sin\gamma \\ &\quad - 1.02 rb_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma) \end{aligned} \tag{26}$$

$$P_{j,UPFC} = rb_{se} V_i V_j \sin(\theta_i - \theta_j + \gamma) \tag{27}$$

$$Q_{i,UPFC} = -rb_{se} V_i^2 \cos\gamma \tag{28}$$

$$Q_{j,UPFC} = rb_{se} V_i V_j \cos(\theta_i - \theta_j + \gamma) \tag{29}$$

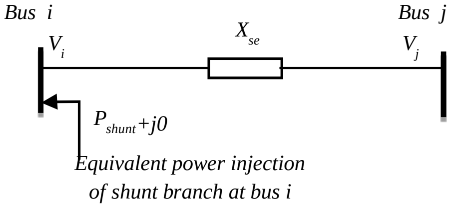


Fig.6.Equivalent power injection of shunt branch.

Finally, UPFC mathematical model can be constructed by combining the series and shunt power injections at both bus *i* and bus *j* as shown in Figure 7. The elements of equivalent power injections in Figure 6 are,[14]

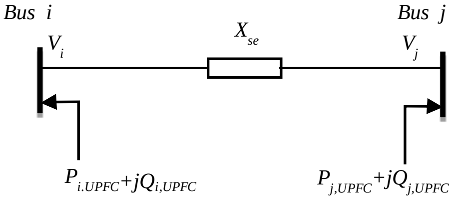


Fig.7.UPFC mathematical model.

2.2.2 The Jacobian matrix

The UPFC injection model can easily be incorporated in a load flow program. If a UPFC is located between node *i* and node *j* in a power system, the admittance matrix is modified by adding a reactance equivalent to X_S, between node *i* and node *j*. The Jacobian matrix is modified by addition of appropriate injection powers. If we consider the linearized load flow model as:[15]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{30}$$

Where H, N, J, L are the elements of jacobian matrix,[9]

$$H_{im} = \frac{\partial P_i}{\partial \delta_m},\ N_{im} = \frac{\partial P_i}{\partial V_m},\ J_{im} = \frac{\partial Q_i}{\partial \delta_m},\ L_{im} = \frac{\partial Q_i}{\partial V_m} \tag{31}$$

In this project a Newton Raphson power flow algorithm is used to solve for the power flow problem in a transmission line with UPFC.

Figure 8 shows the flow chart of the used algorithm.[16]

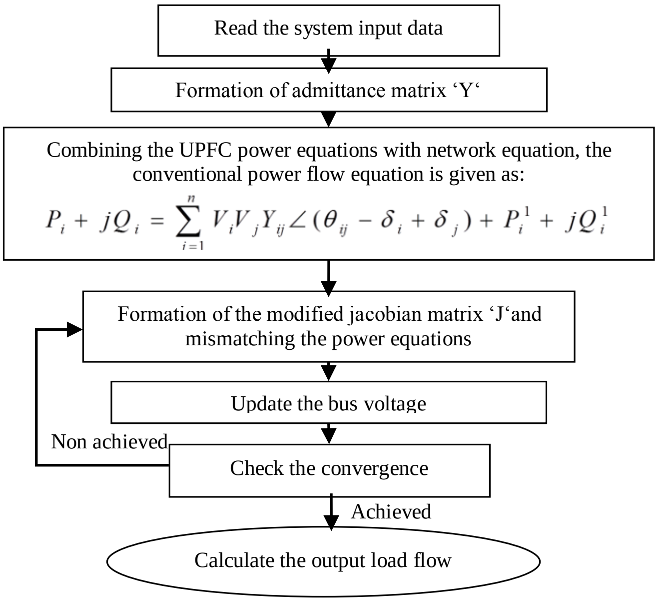


Fig.8.Flow chart of the algorithm [17].

2.3 UPFC Control System

The shunt converter operates as a static synchronous compensator (STATCOM). In summary, the shunt converter controls the AC voltage at its terminals and the voltage of the DC bus. It uses a dual voltage regulation loop: an inner current control loop and an outer loop regulating AC and DC voltages.

Control of the series branch is different from the Static Synchronous Series Compensator (SSSC). In a SSSC the two degrees of freedom of the series converter are used to control the DC voltage and the reactive power. In case of a UPFC the two degrees of freedom are used to control the active power and the reactive power. A simplified block diagram of the series converter is shown below in Figure 9.

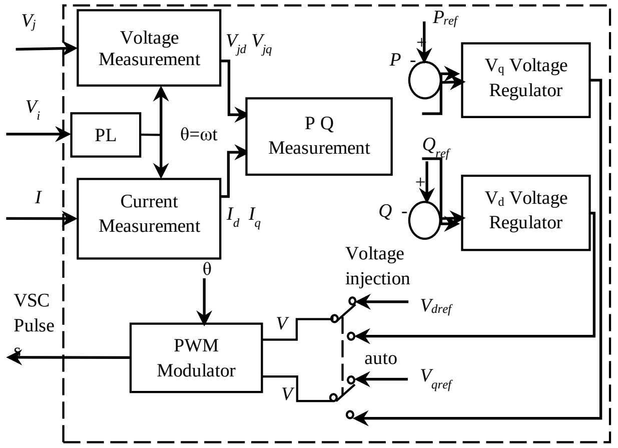


Fig.9.Simplified Block of the Series Converter Control System.

The series converter can operate either in power flow control (automatic mode) or in manual voltage injection mode. In power control mode, the measured active power and reactive power are compared with reference values to produce P and Q errors. The P error and the Q error are used by two PI regulators to compute respectively the V_q and V_d components of voltage to be synthesized by the VSC. (V_q in quadrature with V_i controls active power and V_d in phase with V_i controls reactive power).

3. System under study

The two-area system used in this paper is an 11 Bus multimachine system available in [18].

The system contains eleven buses and two areas, connected by a weak tie between bus 7 and 9. Totally two loads are applied to the system at bus 7 and 9. Two shunt capacitors are also connected to bus 7 and 9 as shown in the Figure 10. The system has the fundamental frequency 60 Hz. The system comprises two similar areas connected by a weak tie, each area consists of two generators, each having a rating of 900 MVA and 20 kV.

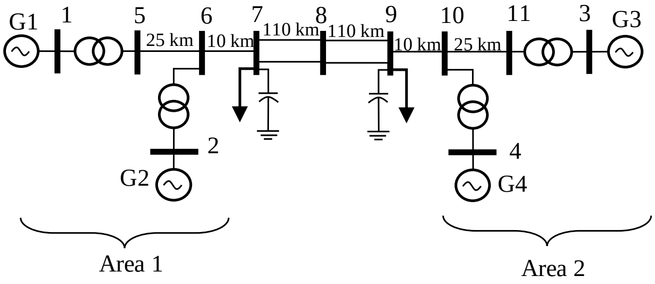


Fig.10.11 bus multimachine test system.

4 Simulation Results

4.1 Case 1

A Newton-Raphson load flow program has been written in MATLAB. The program is applied on the 11 bus AC multimachine test system with the UPFC located between Bus 8 and Bus 9 to control the power flow at the weak tie, and the results are compared to the test system without the UPFC, to see its effect on the power flow in the steady state conditions.

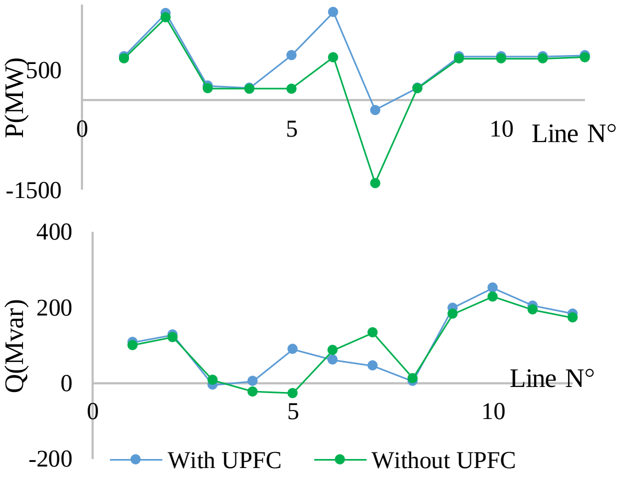


Figure 11 Active and reactive power flow with and without the UPFC

As shown in Figure 11 the UPFC change completely the power flow among the power system. the active power flow without the UPFC shows that the line 7 of the weak tie is overloaded, it channels around 1400 MW, this overload of the line 7 has been decreased significantly by including the UPFC and therefore the line 7 carries an acceptable power around 160 MW. The remaining power flow is redirected to the lines 5 and 6; also, the reactive power flow of the line 7 where the UPFC is installed has been decreased by increasing the power flow through lines 5 and 6, so the UPFC relieve the overload of line 7 by allowing a better use of under-loaded lines (5 and 6).

4.2 Case 2

A three-phase fault of 50 ms duration is created at the middle of the transmission line connecting the Bus 8 and 9 at t=1s, The performance of the conventional PI controller, in damping the oscillations of the generators and the active power and nodal voltages are presented in Figure 12.

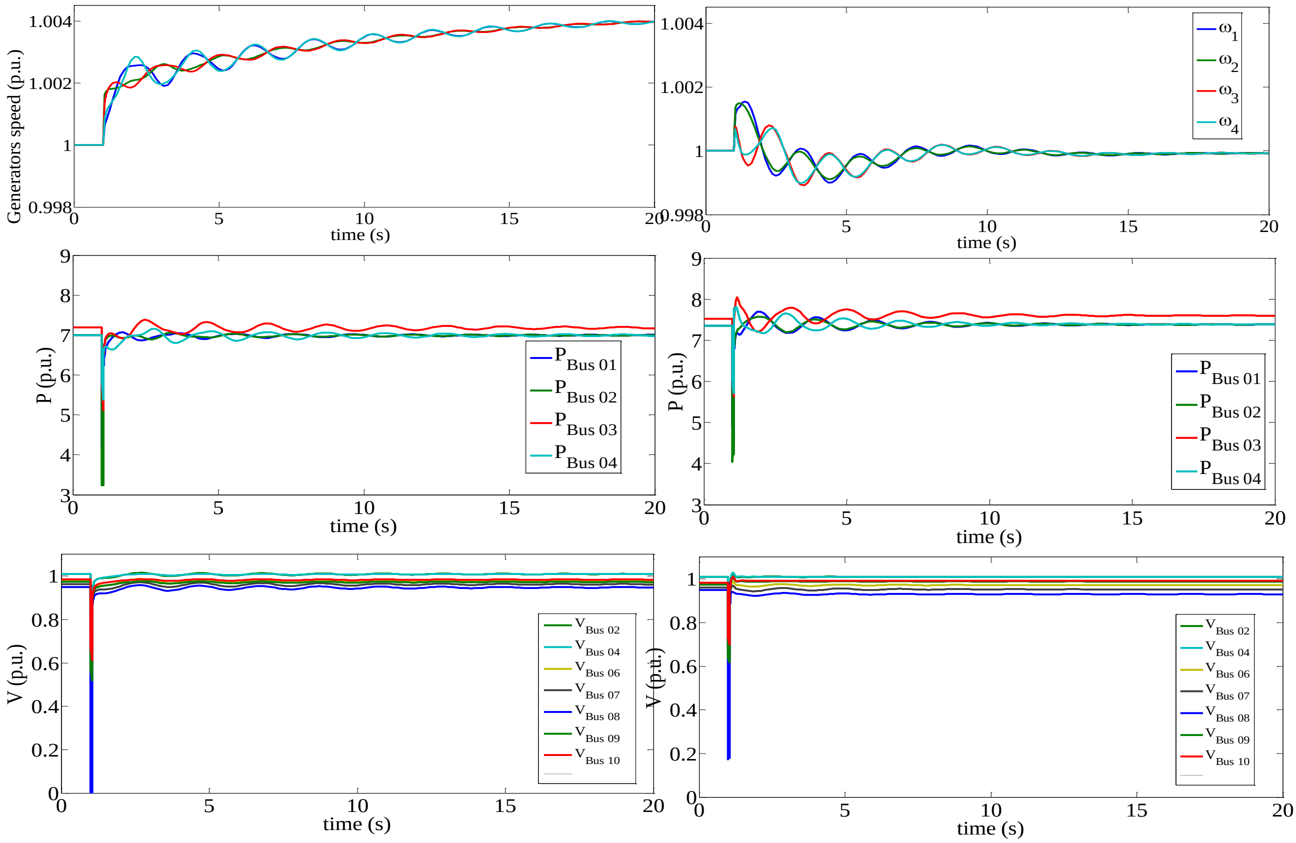


Fig.12.Generators speed and active power and voltage profile with and without the UPFC

Without the UPFC, it is clear that the generators speed is tripped because of the fault, and continue to diverge from its nominal value. The active power and the bus voltages also oscillates after the fault, while with the UPFC the generators speed fluctuates and recover its nominal value around t=12s, the same effect is observed on the active power and the voltage. The steady state recovery time after the fault is considerably reduced by the UPFC.

5. Conclusion

This paper presents the improvement of power system steady state and dynamic performance by the UPFC. Simulation results show the effectiveness of UPFC to control the real and reactive powers. It is found that there is an improvement in the real and reactive powers, through the transmission line when UPFC is introduced.

Under fault condition, settling time of the system can be reduced considerably by the UPFC, making the system stable with fewer oscillations.

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