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Voltage Sourced Converter (VSC) based on multiple FACTS controllers for the improvement of power quality

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Abstract. This paper deals with the problems of improving power quality in electrical power grids by using multiple FACTS devices like STATCOM, SSSC and UPFC. The present scenario will focus on the working of the various FACTS family under different types of generator faults that can cause any other transmission lines to be overflowed. The simulation analysis of the proposed model being tested for power grid consists of two-area with 500-kV equivalents connected across the transmission line. The effect of active power, reactive power and voltage responses are studied.

Key words
System stability, FACTS controllers, STATCOM, SSSC, UPFC.

1. Introduction

Power quality issues like voltage sags, swells and harmonics may cause system to shut down or tripping of breakers owing to large current imbalances [1-2]. Nowadays, the technical benefits of flexible alternating current transmission system (FACTS) devices have been investigated in areas of power engineering, which have many advantages such as improving the static/dynamic stability and power quality of AC network as well as maintaining system security [3-8]. FACTS family like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC) and unified power flow controller (UPFC) can be connected to a transmission line at any suitable location in series, in parallel, or in a combination of series-parallel [9-12].

This paper aims towards power quality improvement using FACTS controllers to control various parameters of transmission line network. The paper is structured as follows: Section 2 presents the configuration and modeling analysis of various types FACTS controllers. Simulated system modeling without connecting any FACTS device are addressed in Section 3. Test systems, simulation results and discussion are illustrated in Section 4. Finally, research conclusions are given in Section 5.

2. Power Quality Compensation

Many compensation techniques for improving the power quality, such as the cancellation of harmonics, optimal placement of capacitor banks/sizing, etc. [13], have been proposed to keep the harmonic voltages and currents within the proposed levels. The FACTS family concept is based on the use of power electronics to solve the power quality problems and to control the active/reactive power flow and the voltage in the transmission network [14]. Power flow is a function of the transmission line impedance, the magnitude of sending/receiving end voltages and the phase angle between them. By controlling one or a combination of power flow arguments, it is possible to control active and reactive flow of power in the transmission line. Figure 1 illustrates a simple power system with impedance connecting between two-area power systems. Suppose that system I is a sending-end with voltage V_1 and system II is a receiving-end with voltage V_2, β_1 and β_2 are the phase angles of the sending-end and receiving-end voltage sources.

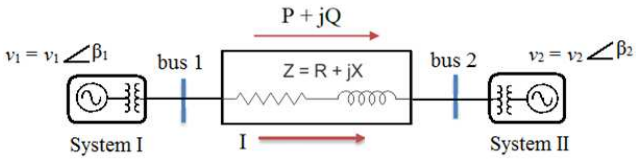


Fig. 1: Simplified power system

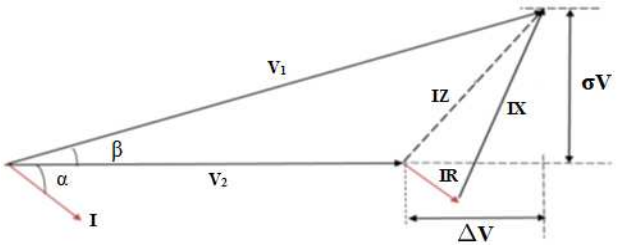


Fig. 2: Vector line diagram

According to Figures 1 and 2, the equations for describing the active and reactive power flows at the receiving-end and sending-end voltage sources can be written as follows:

$$\begin{cases} \Delta V = IZ\cos\alpha = V_1\cos\beta - V_2 \\ \sigma V = IZ\sin\alpha = V_1\sin\beta \end{cases} \quad (1)$$

$$I = \frac{V_1 - V_2}{Z} = \frac{V_1\angle\beta_1 - V_2\angle\beta_2}{Z} = \frac{\Delta V + j\sigma V}{Z} \quad (2)$$

For a transmission line connecting buses (1) and (2) with stiff bus voltages $V_1\angle\beta$ and $V_2\angle 0$, the complex power developed at sending-end side can be calculated as follows:

$$S_1 = \frac{V_1V_2}{R^2+X^2}\left(R\left[\frac{V_1}{V_2}-\cos\beta\right]+X\sin\beta + jX\left[\frac{V_1}{V_2}-\cos\beta\right]-jR\sin\beta\right) \quad (3)$$

$$P_1 = \frac{V_1V_2}{R^2+X^2}\left(R\left[\frac{V_1}{V_2}\right]-\cos\beta\right)+X\sin\beta$$
$$Q_1 = \frac{V_1V_2}{R^2+X^2}\left(X\left[\frac{V_1}{V_2}\right]-\cos\beta\right)-R\sin\beta \quad (4)$$

Similarly, the complex power developed at receiving-end side can be calculated as follows:

$$S_2 = \frac{V_1V_2}{R^2+X^2}\left(R\left[\frac{V_2}{V_1}-\cos\beta\right]-X\sin\beta + jX\left[\frac{V_2}{V_1}-\cos\beta\right]+jR\sin\beta\right) \quad (5)$$

$$P_2 = \frac{V_1V_2}{R^2+X^2}\left(R\left[\frac{V_2}{V_1}\right]-\cos\beta\right)-X\sin\beta$$
$$Q_1 = \frac{V_1V_2}{R^2+X^2}\left(X\left[\frac{V_2}{V_1}\right]-\cos\beta\right)+R\sin\beta \quad (6)$$

where V_1 and V_2 are the values of voltages, β_1 and β_2 are phase angles of the voltage at buses 1 and 2, respectively.

For simplicity, the voltage phase angles are chosen such that $\beta_2 = 0$ and the difference between the phase angles is $\beta = \beta_1 - \beta_2 = \beta_1$ as depicted in Fig. 3. By putting $R = 0$ in Eq. 4, the active and reactive power can be written as:

$$P_1 = \frac{V_1V_2\sin\beta}{X};\quad Q_1 = \frac{V_1^2}{X} - \frac{V_1V_2\cos\beta}{X} \quad (7)$$

Also from Eq. 6, the active and reactive power can be written as follows:

$$P_2 = -\frac{V_1V_2\sin\beta}{X};\quad Q_2 = \frac{V_2^2}{X} - \frac{V_1V_2\cos\beta}{X} \quad (8)$$

The above active power expressions are equal but in opposite direction, as it is a lossless system $R = 0$. In this case, maximum active power is transferred at a phase angle of $\beta = 90$ as shown in Fig. 3. However, this angle decreases when resistive shunt loads and transmission line losses are included.

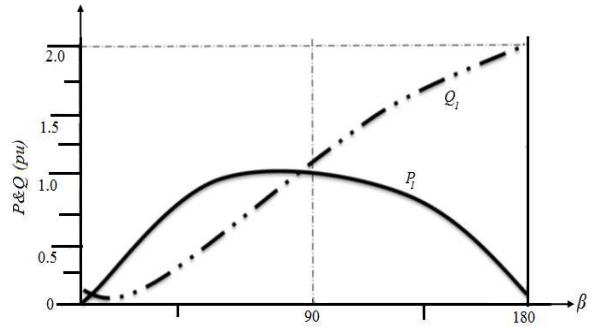


Fig. 3: P & Q characteristic curve with phase angle β

The load flow control in power networks is one of the crucial factors affecting the development of recent power systems. There are different fundamental limits on how power can be transmitted along a transmission line and how to solve the above mentioned difficulty. Nowadays, FACTS controllers are already in operation throughout the world. They are mainly used for improvement of fast static/dynamic behavior and utilization of available cheap power of the power network [15].

3. FACTS Devices Configuration

A. STATCOM system

Fig. 4 depicts the circuit that uses power electronics to control power flow and improve transient stability on power networks. STATCOM is basically a shunt connected device which consists of a magnetic coupling, voltage-sourced converter (VSC), DC capacitor and control unit. Therefore, it usually regulates system voltage by controlling the amount of reactive power injected into or absorbed from the power grid [16-17]. The VSC uses power electronic switches such as GTO's or IGBT's to synthesize the voltage V_s from a DC voltage source. The corresponding equations of active and reactive power with the grid can be expressed as:

$$P = \frac{V_K V_S \sin\psi}{X_S} \quad (9)$$

$$Q = \frac{V_K(V_K - V_S\cos\psi)}{X_S} \quad (10)$$

where V_k is the System bus voltage magnitude, V_s the STATCOM output voltage magnitude, X_s the equivalent impedance between STATCOM and the system, and ψ the phase angle of V_k with respect to V_s.

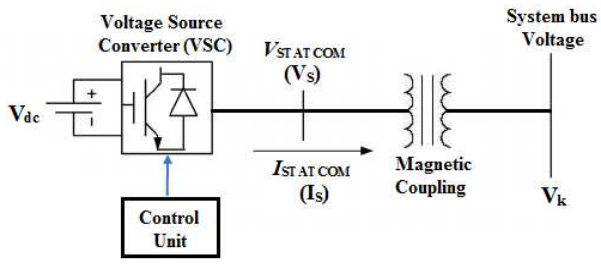


Fig. 4: STATCOM System Configuration

If $V_s > V_k$ then the reactive current flows from the converter to the AC system through the magnetic coupling by injecting reactive power to the AC system. If $V_s < V_k$ then current flows from AC system to the converter by absorbing reactive power from the system. Finally, if $V_s = V_k$ then there is no exchange of reactive power. The amount of reactive power exchange can be written as:

$$Q = \frac{V_K (V_K - V_S)}{X_S} \tag{11}$$

B. SSSC System

SSSC employs a voltage sourced converter serially connected to a transmission line through an insertion transformer as illustrated in Fig. 5. SSSC operates in the similar way as the STATCOM device, but it is connected in series instead of parallel [18-19].

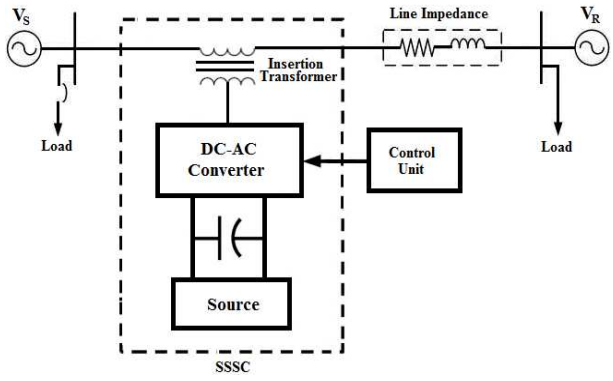


Fig. 5: SSSC System Configuration

When operated with the proper energy supply, the SSSC can inject a voltage component being of the same value but opposite in phase angle with the voltage developed across the line. The SSSC is typically applied to correct the voltage during a fault in the power grid. However, it has several advantages during normal state such as power factor correction, power flow control and harmonic distortion reduction by active filtering [20]. The active transmission power flow can be expressed as follows:

$$P = \frac{V^2 \sin\gamma}{X} \tag{12}$$

with V being the sending and receiving end voltages (assuming $V = V_S = V_R$), X the equivalent impedance of the line, and γ the power angle.

C. UPFC System

UPFC is the most versatile multi-variable FACTS family which consists of a shunt and series converter coupled through a common DC terminal as depicted in Fig. 6. The VSC1 controls the bus voltage/shunt reactive power and the DC link capacitor voltage while VSC2 controls the transmission line active/reactive power flows by injecting a series voltage of adjustable magnitude and phase angle [21]. The active and reactive corresponding power equations can be calculated as follows:

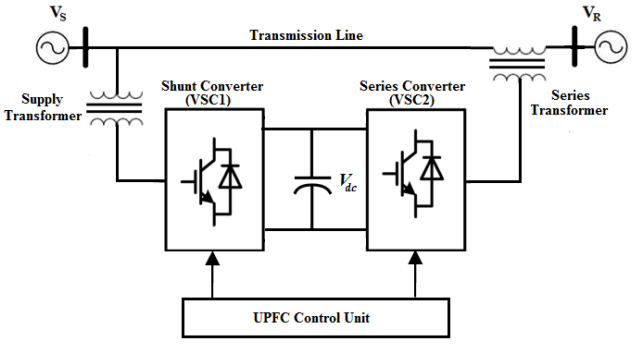


Fig. 6: UPFC System Configuration

$$P = \frac{V_1 V_2 \sin\alpha}{X} \tag{13}$$

$$Q = \frac{V_2 (V_1 - V_1 \cos\alpha)}{X} \tag{14}$$

UPFC is one of the FACTS controllers that can control the power system parameters such as terminal voltage, line impedance and phase angle [22]. UPFC has different applications such as generating/absorbing active and reactive power, and improving the transient stability.

4. Numerical testing using Simulink program

This study investigates power grid consisting of two-area 500 kV equivalents connected to a transmission line and the total transmitted power on the transmission line is 930 MW by using Matlab/Simulink program under different faults conditions as depicted in Fig. 7.

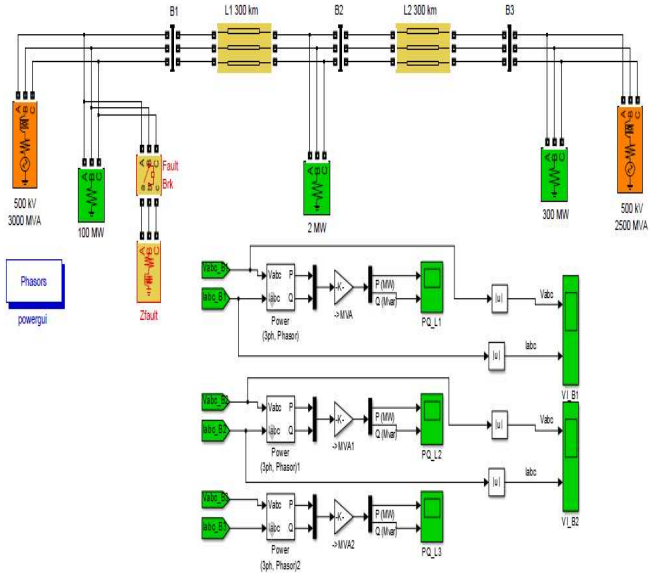


Fig. 7: Main system Simulink model

A. STATCOM controller

The STATCOM used for midpoint voltage regulation is located at the midpoint of the line bus B2 and has a rating of 100 MVA. The fault resistance is 0.001 Ω. The two-area power system responses are investigated in terms of active power, reactive power and voltage, respectively. The STATCOM simulation model is shown in Fig. 8 and the associated system parameters are given in Appendix.

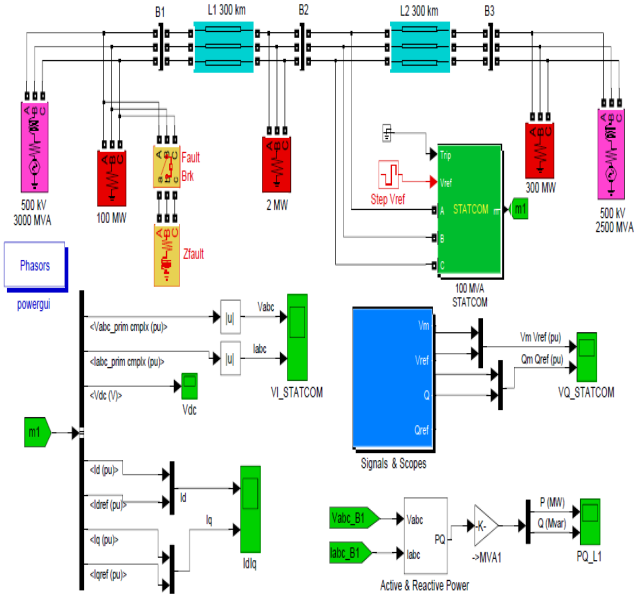


Fig. 8: STATCOM system simulation model

Fig. 9 illustrates the reference voltage V_{ref} along with the measured positive-sequence voltage V_m at the STATCOM bus and the reactive power Q_m which is absorbed (*+Ve*) value or generated (*-Ve*) value by the STATCOM.

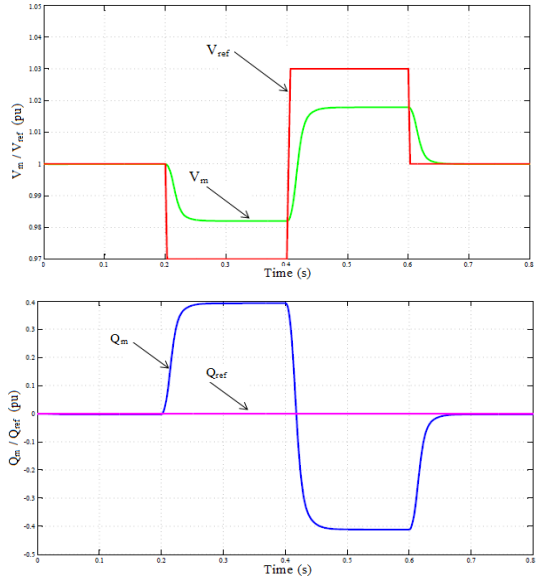
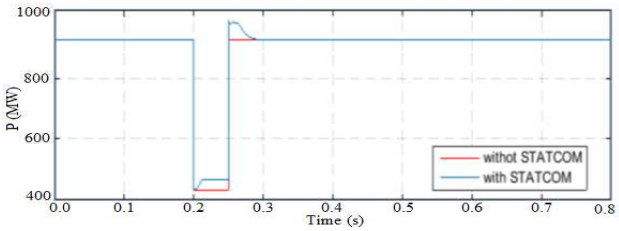


Fig. 9: Performance of STATCOM

Fig. 10 illustrates the system responses under three-line fault. In this case, the active power generated from the system without STATCOM is more than the system with STATCOM. Also, the reactive power generated from the system with STATCOM is higher than the system without STATCOM, because the active power is decreased.



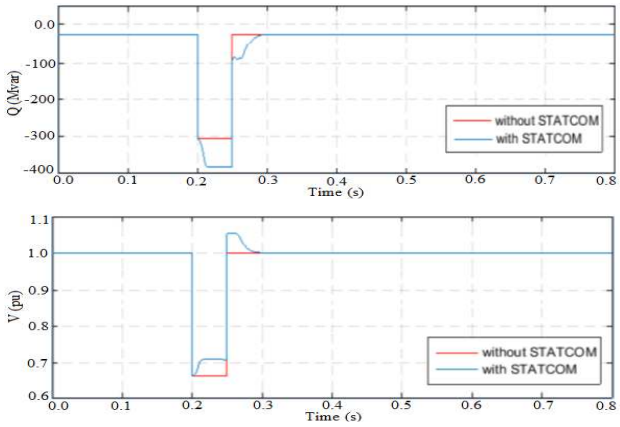


Fig. 10: Active, reactive power and voltage response

B. SSSC Controller

The system model with SSSC has been simulated in Matlab/Simulink environment as depicted in Fig. 11.

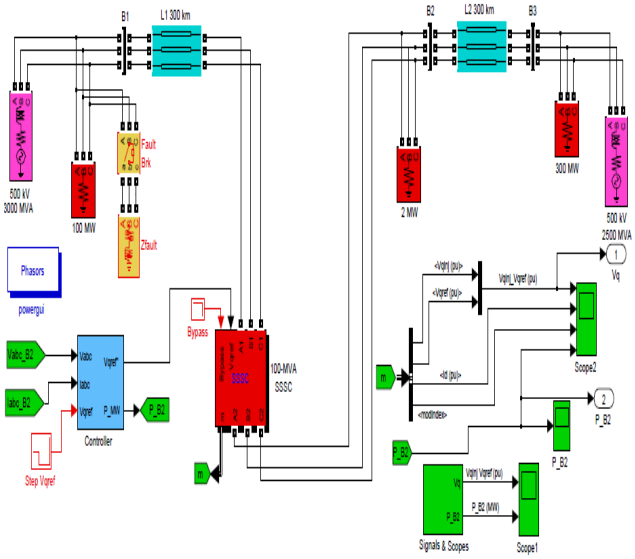
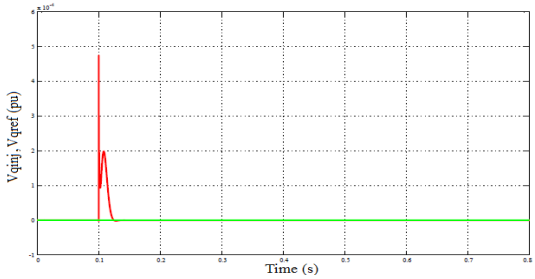


Fig. 11: SSSC system simulation model

With the system running under different fault conditions for the SSSC device. The fault resistance was 0.001 Ω. The SSSC is located in series with the line and has a rating of 100 MVA. The two-area power system responses are investigated here in terms of the active power, reactive power and voltage, respectively. The parameters of SSSC system is in Appendix. Fig. 12 illustrates the reference voltage V_{qref} along with the measured injected voltage V_{qinj} by the SSSC and the active power flow of the SSSC system.



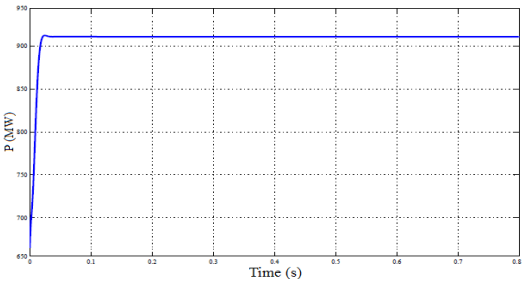


Fig. 12: Performance of SSSC

Fig. 13 illustrates the system responses under three-line fault. The active power generated from the system without SSSC is more than that with SSSC and the reactive power generated from the system with SSSC is more than that without SSSC, because the active power is decreased.

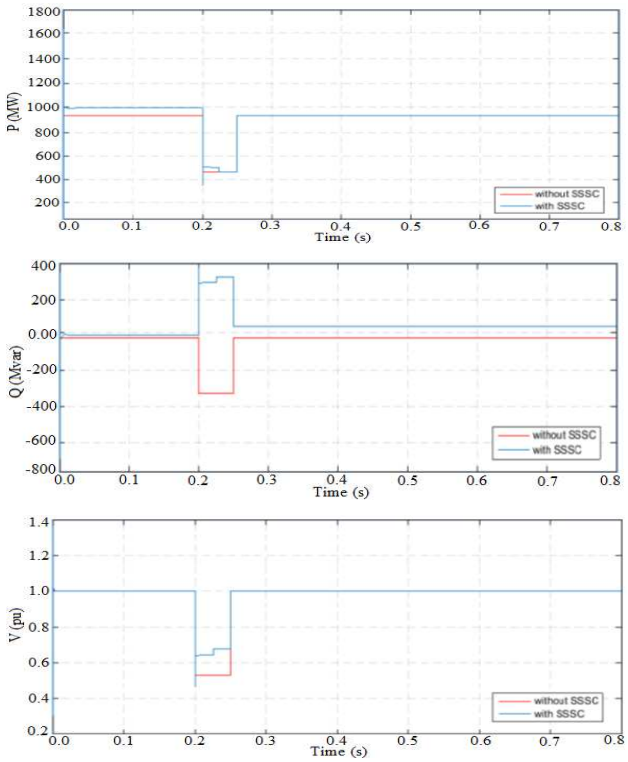


Fig. 13: Active, reactive power and voltage response

C. UPFC Controller

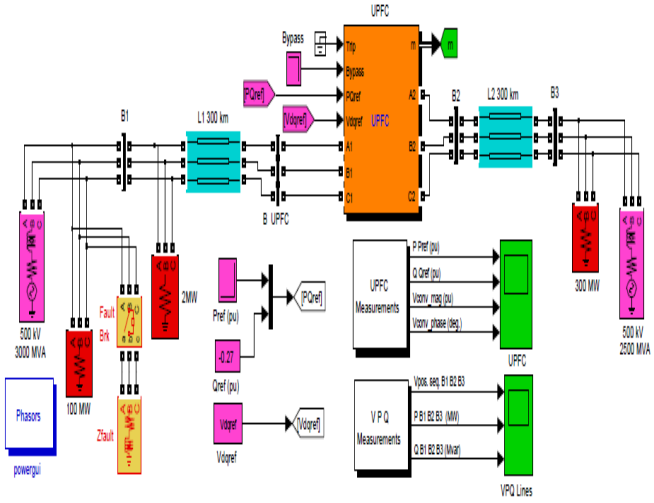


Fig. 14: UPFC System Simulation Model

The system model with UPFC has been simulated in Matlab/Simulink environment as depicted in Fig. 14. With the system running under different fault conditions for the UPFC device. The fault resistance was 0.001 Ω. The UPFC is used to control the power flow in a two-area grid 500 KV equivalent connected to a transmission line and consists of two 100 MVA based on shunt and series converters. Fig. 15 depicts the performance of UPFC system response for the variations and reference of active power and reactive power, respectively.

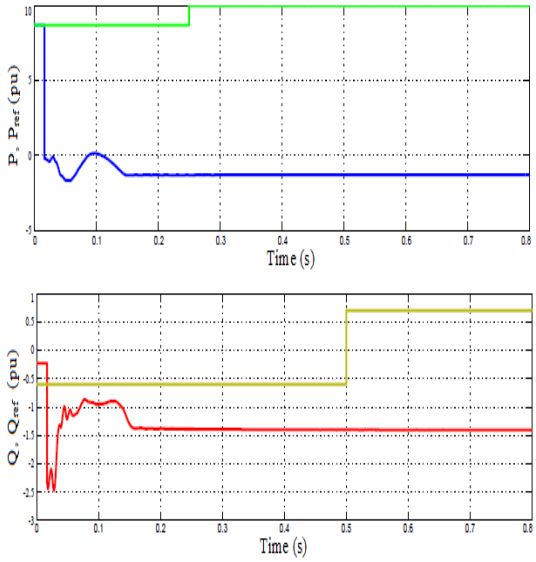
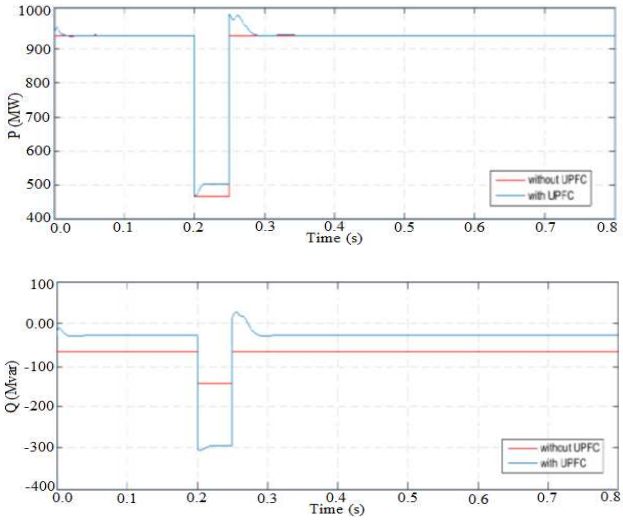


Fig. 15: Performance of UPFC

The two-area power system responses are investigated in terms of the active power, reactive power and voltage, respectively. Fig. 16 illustrates the system responses under three-line fault. The power losses caused from the system without UPFC is more than those with UPFC. The active power generated from the system without UPFC is more than that with UPFC, but the reactive power generated from the system with UPFC is more than that without UPFC, because the active power is decreased.



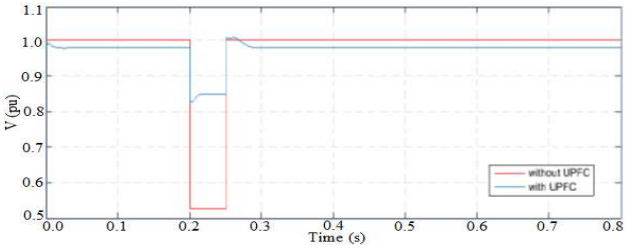


Fig. 16: Active, reactive power and voltage response

5. Conclusions

This work has studied the improvement of power quality in a two-area interconnected power system under different fault conditions in terms of active power, reactive power and voltage responses. The modeling, analysis and simulation of the above scenario, with or without FACTS family STATCOM, SSSC and UPFC controllers, have been done by using MATLAB/Simulink program. The numerical results have shown that the FACTS family controllers can improve effectively power quality, reduce the power losses, and are faster as compared to systems without FACTS controllers. The future work will be oriented towards applying hybrid FACTS family and the associated optimal location based control techniques for the improvement of power quality.

APPENDIX

Design Parameters:

- Rating of STATCOM = 100 MVA with system frequency = 50 Hz and source voltage = 500 kv.
- Transmission line length = 600 km, Total impedance of STATCOM = 0.22 pu and Capacitance = 375 µf
- DC link voltage = 40 kV and Frequency modulation = 1.68 kHz
- Proportional gain = 5 and Integral gain = 1000
- Rating of SSSC = 100 MVA, Rating of UPFC = 500 Kv and 100 MVA

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