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Unified Power Flow Controller for Efficient Management of Power Flow in a Five Bus System during Switching of a VAR Load

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Abstract—This paper illustrates the efficacy of UPFC, in controlling power flow in a transmission system. Usefulness of a UPFC in controlling the power flow during normal operation as well as during a sudden demand in power on connecting a high Var load is demonstrated. Performance of a 5 bus transmission system is simulated with and without a UPFC, using MATLAB software. It is proved that the introduction of UPFC not only improves the power flow but also improves the voltage regulation without compromising the dynamic performance of the system.

Index Terms— Minimum Compensation, Phase Regulation, Power flow, Reactive Power, UPFC, Voltage Regulation ,VSC..

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1 INTRODUCTION

ECONOMIC growth is constantly driving the demand for power in India. While power demand is rising, generation from existing power stations or renovated stations are not increasing in proportion with the demand. As the installation of the new power plants are getting entangled with several roadblocks, be it the environmental clearance, the coal linkage or the financial tie ups, the immediate solution seems to be the enhancement of capabilities of the existing transmission lines. Until recently, with the exception of SVC, all the plant components used in high voltage transmission to provide voltage and power flow control, were equipment based on the electromechanical topology, which severely impaired the effectiveness of the intended control actions, particularly during fast changing operating conditions. This situation has begun to change, building on the operational experience afforded by many SVC installations. Due to the tremendous growth in power electronic devices and their control, a vast array of new power electronic based controllers has been developed. FACTS devices have been extensively used for the improvement in the power transmission capability of a transmission line [1]. FACTS devices made their debut in 1980s and have grown with the introduction of the Voltage Source Converters in 1990s. The most versatile of this group is the Unified Power Flow Controller (UPFC). The UPFC allows simultaneous control of active and reactive power flows and voltage magnitude at the UPFC terminals. Thus we can say that it provides three degrees of freedom; voltage regulation, series compensation along with phase shifting [2][3]. The UPFC helps to regulate the power flow, thus allowing the loading of transmission lines near to their thermal limits [5]-[9]. In addition to these, UPFC has the capabilities of mitigating the system oscillations, improving the transient stability and providing the voltage support [9]- [11]. Many studies and analysis have been carried about the performance of UPFC since its introduction [12]-[19]. The studies indicate that UPFC can be used for controlling the real and reactive power flows.

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2 UNIFIED POWER FLOW CONTROLLER

The UPFC consists of two voltage source converters (VSC), one series and the other one shunt, connected to the transmission line through a series transformer and a shunt transformer. The basic VSC consists of six switches made up of six IGBTs with antiparallel diodes across them. The two converters share a common DC link by means of a capacitor. The schematic of a UPFC is depicted below.

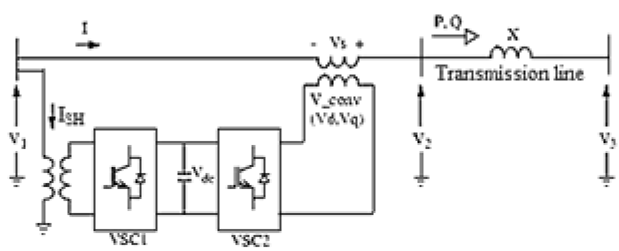

Fig.1 UPFC Schematic diagram

3 OPERATION OF UPFC

When we go through the FACTS Controllers literature, the most common operation mode of a shunt Voltage Source Converter is to regulate the bus voltage and of a series Voltage Source Converter is to control the real power flow on the transmission line. In a UPFC, when a shunt VSC and a series VSC are combined at their DC bus, the line reactive power

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flow can also be controlled.

If we consider each converter separately, we can see that the shunt converter working alone can be considered as the Static Synchronous Compensator (STATCOM). This is capable of supplying or absorbing real power to the transmission line by adjusting the phase shift between the converter output voltage and the voltage at the point of connection of the shunt converter the to the transmission line. By adjusting the amplitude of the output of the converter to be above or below of that of the bus, the current can be made to flow from the converter to the bus or from the bus to the converter indicating reactive power generation or absorption. Thus the shunt converter is capable of exchanging the real power as well as the reactive power with the transmission line.

The series converter is nothing but the Static Synchronous Series Compensator (SSSC) when acting alone. As the name indicates, it is connected in series with the transmission line through the series transformer. The output of the converter is a voltage of variable magnitude and phase angle. Thus the series converter can vary the effective impedance of the transmission line by injecting a voltage of appropriate magnitude and phase angle with reference to the line current. Thus it is capable of exchange of real as well as reactive power with the transmission line.

When these two converters are made to share the same DC source, we get the most versatile FACTS controller, namely the UPFC. In this, the series converter is made to inject a series voltage VS with a phase angle) thus exchanging the real and reactive power with the lines. There cannot be any exchange of reactive power between the converters due to the DC link. The role of shunt converter is mainly to meet the real power requirement of the series converter.

Thus the UPFC can be connected at any location in the network and the voltage at the point of connection can be maintained constant thereby achieving voltage regulation.

4 Operating Modes Of UPFC

As mentioned above, UPFC connected in a system can provide voltage regulation as well as control of real and reactive power flow. The series and shunt regulators are responsible for this achievement. Depending upon which converter is utilised, we can have different modes of operation for the UPFC.

4.1 Shunt Converter

The shunt converter can inject a variable shunt voltage with the transmission line such that the current flow to the shunt converter has a real component which can produce the real power. This real power meets the power loss in the series converter. The reactive power exchange between the shunt converter and transmission line can independently provide the shunt compensation and hence maintain the voltage constant, thereby providing voltage regulation. The shunt reactive current can be made leading or lagging to meet the required capacitive or inductive Var request. Thus we can see that the shunt converter can be operated either in Automatic voltage regulation mode or Var control mode.

4.2 Series Converter

The powerflow in a transmission line is controlled by adding a series voltage Vse of certain amplitude and with a particular phase shift φ to Vs. Thus we can get a new line voltage with different magnitude and phase shift. As we vary the angle φ, the phase shift between Vs and VR also varies. Thus the series converter is controlled to inject a voltage of variable magnitude as well as phase angle. Depending on the phase angle values we can realise different modes of operation for the UPFC. If the injected voltage is in phase with the sending end voltage, we can achieve voltage regulation. By injecting a voltage orthogonal to the line current, the net voltage drop across the line impedance can be controlled thereby achieving reactive compensation. By injecting a voltage Vse of desired magnitude, we can cause a shift in the phase angle of the sending end voltage Vs[3][4].

By controlling the terminal voltage, phase angle and line impedance simultaneously, the UPFC can be made to perform power flow control.

Thus there can be four modes of operation for the series converter as follows:

Direct voltage injection mode
Line impedance compensation mode
Phase angle regulation mode
Automatic power flow control

5 Power Flow Equations

The UPFC is connected at the sending end of a bus whose voltage has to be regulated. The converter can be shown by a variable voltage source representing the voltage injection.

If VS represents the sending end voltage, VR the receiving end voltage and Vse the voltage injected by the UPFC, then we can find the power flows in the transmission line as follows.

Without UPFC,

$$S_R = V_R \times I_L$$

$$= V_R \left(\frac{V_S \angle\delta - V_R}{R + jX} \right)$$

$$P_o = \frac{V_S V_R \sin\delta}{X} \qquad Q_o = \frac{V_S V_R \cos\delta - V_R{}^2}{X}$$

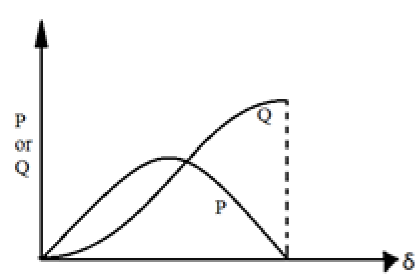

Fig. 2. Power Flow

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The UPFC can be connected anywhere in the line. Here it is connected at the sending end bus to regulate the power flow. The series converter injects a voltage Vse to make the voltage at the receiving end regulated also. The shunt converter has a voltage V_{sh} at its ac terminals.

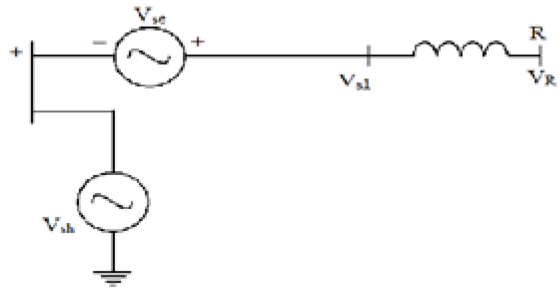

Fig.1 UPFC in a transmission line.

When the UPFC is connected in the bus where it is required to improve the power flows, the equations get modified as written below.

$$S_R = V_R \times I_L^{\,*}$$

$$= V_R \left(\frac{V_S\angle\delta + V_{se}\angle\varphi_{se} - V_R}{R + jX}\right)$$

$$P_o' = \frac{V_S V_R \sin\delta}{X} + \frac{V_{se} V_R \sin\varphi_{se}}{X}$$

$$= P_o + P_{upfc}$$

$$Q_o' = \frac{V_S V_R Cos\delta - V_R^{\,2}}{X} + \frac{V_{se} V_R \cos\varphi_{se}}{X}$$

$$= Q_o + Q_{upfc}$$

Where P_{upfc} and Q_{upfc} are the additional power flows due to the insertion of UPFC in the line.

$$P_{upfc} = \frac{V_{se} V_R \sin\varphi_{se}}{X}$$

$$Q_{upfc} = \frac{V_{se} V_R \cos\varphi_{se}}{X}$$

This is the most simplified form of representing the UPFC [11]. This is an effective model, but it lacks control flexibility.

A more flexible model can be derived by considering the two converters as two coordinated voltage sources. The active power demand by the series converter is met by the shunt converter. If the converter switches are assumed to be lossless, the injected active and reactive powers can be written individually for shunt and series converters separately.

6 Simulation Results

For studying the behaviour of UPFC, a 5-bus system with UPFC connected between buses 2 and 3 is considered. It is required to control the active and reactive power flows in the bus3. The UPFC consists of 100KVA IGBT based voltage source converters. The series converter is required to inject a maximum voltage of 10% of the line voltage ie. 50KV. A high demanding load of both real and reactive power requirements is suddenly switched to the system and the change in the bus voltages and real and reactive power flows are studied without UPFC and then connecting the UPFC to the bus. The simulation is done using MATLAB software and the results are shown in figures 4 and 5.

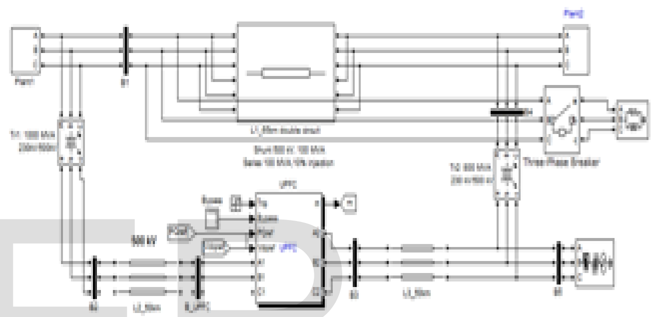

Fig.3 UPFC Simulation Circuit

It can be seen that in the absence of UPFC when the load of 600MW and 1000MVAR is suddenly switched to the system, the voltage of bus3 suddenly dips to 477.3KV. When the UPFC is connected to the bus3, we can see that by injecting a voltage of 1pu, the bus3 voltage can be regulated at 494.3KV. Even the power flow is found to be improved from a low value of 82.9MW to 121.6MW thus proving the usefulness of UPFC in improving the performance of transmission lines.

TABLE I
SYSTEM DETAILS

Sl. No	Test System Details		
1	Generators	Plant1 Plant2	1000MW 1200MW
2	Line inductance	L1 L2 L3	66.95mH 46.685mH 46.685Mh
3	Transformers		1000MVA 800MVA
4	Load	Load1 Load2	200MW 600MW, 600MVar

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5	UPFC	Series Converter Shunt Converter	10% injection (100MW) 1pu

When comparing the simulation results, we can see that there is considerable improvement in the voltage levels and power flow when the UPFC is connected in the system. Figure 4(a) represents the voltage levels of the five buses before the application of a highly demanding load. We can see that all the bus voltages are within the limit of regulation.

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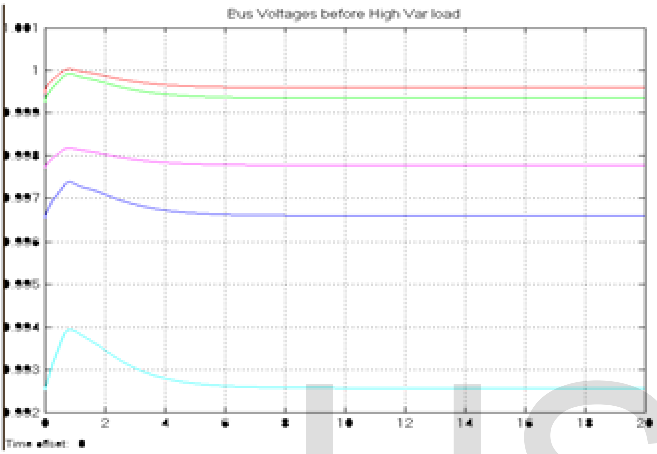

Fig 4a. Bus voltages before connecting the load

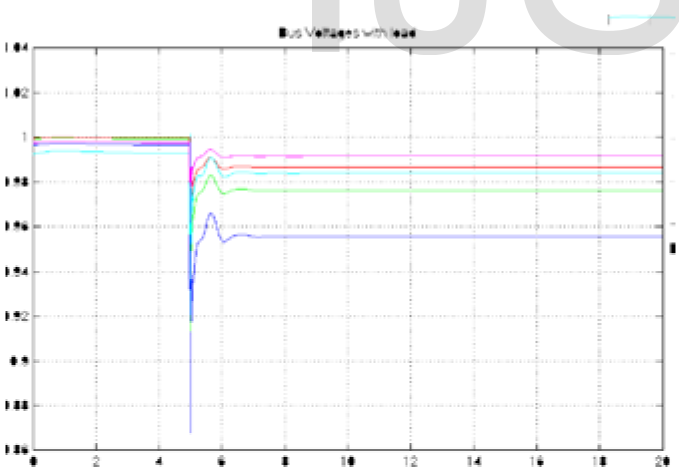

Figure4 b.Bus voltages with 1000 MVar load

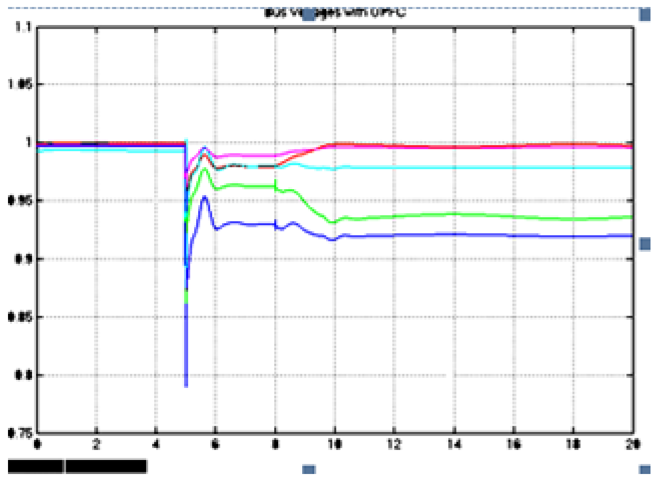

Figure4.c. Bus voltages with UPFC

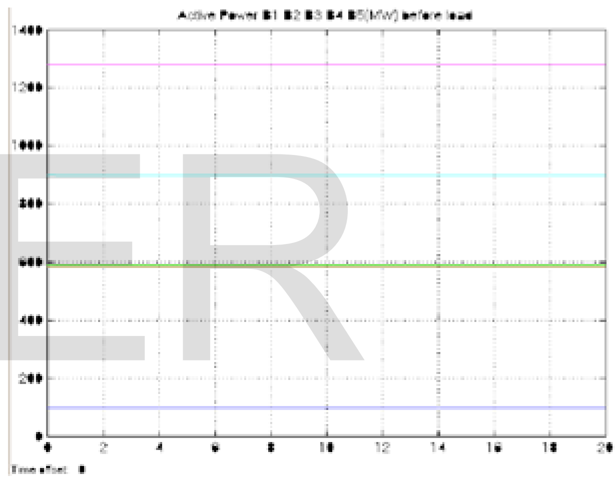

Figure 5a. Active Power flow before load switching

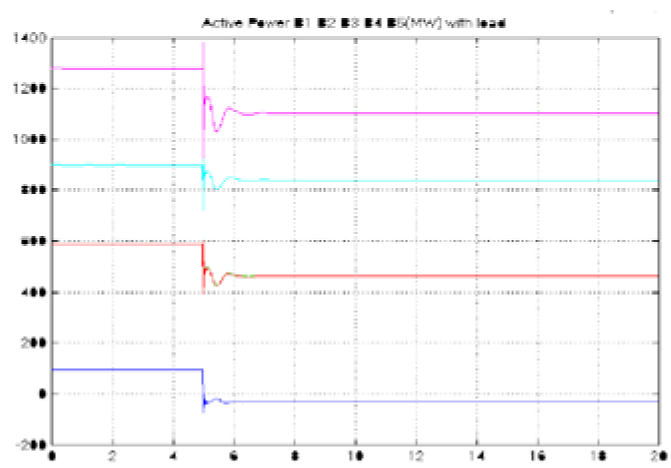

Fig 5.c Active power flow when load is switched

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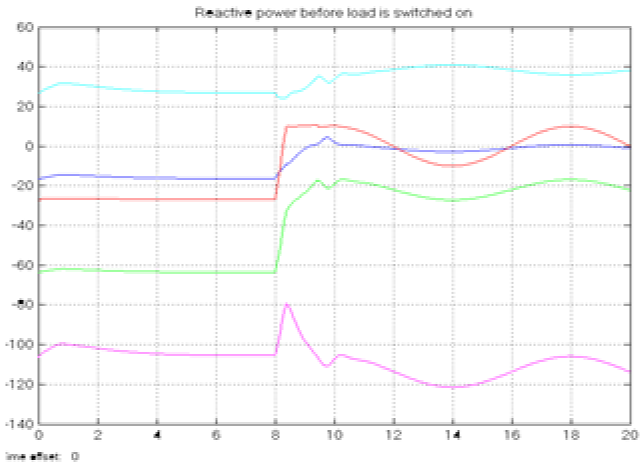

Fig 6.a Reactive power flow

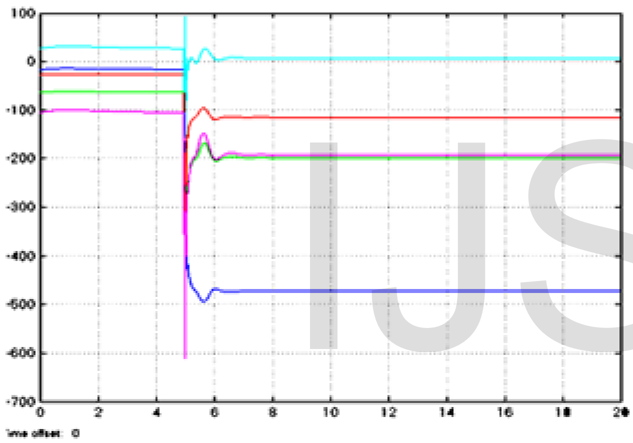

Fig 6.b Reactive power flow with load

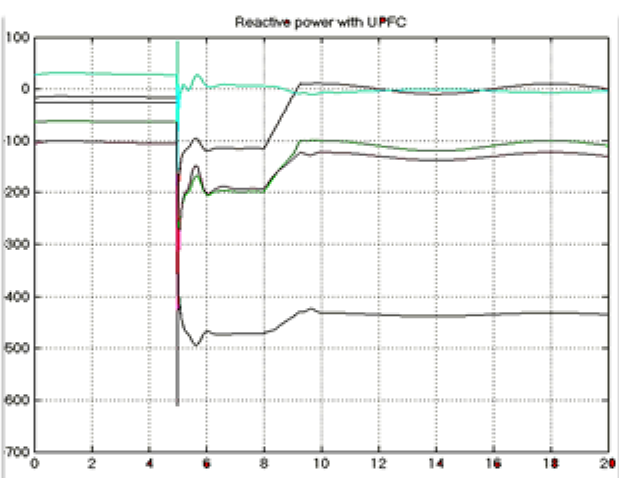

Fig 6.c Reactive power flow with UPFC

7 Conclusions

In this paper, MATLAB software is used to simulate the UPFC model connected to the bus-3 in a 5-bus transmission system. The system is simulated to prove the effectiveness of UPFC in regulating the voltage as well as improving the power flow through the transmission line where sudden switching of highly reactive load is found to be deteriorating the quality of power transmission. The experimental results can be validated for different positioning of UPFC in other lines.

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