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Enhancement of Active and Reactive Power Flow Control over the Transmission Line using UPFC

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***Abstract*— with the growing demand of electricity, at times, it is not possible to erect new lines to face the situation. Flexible AC Transmission System (FACTS) uses the thyristor controlled devices and optimally utilizes the existing power network. FACTS devices play an important role in controlling the reactive and active power flow to the power network and hence both the system voltage fluctuations and transient stability. This paper proposes the Unified Power Flow Controller (UPFC) as a strong candidate to provide a full dynamic control of Power transmission operating parameters: voltages, line impedance, and phase angle under normal and fault conditions. Simulink model composed for 4 bus system equipped with UPFC to illustrate the control features of this device and their influence to improve system stability. Digital simulation using MATLAB/SIMULINK is done and the results are presented. The effect of STATCOM and SSSC on real power, reactive power and the voltage is also presented.**

Key words: FACTS, UPFC, STATCOM, SSSC, Power flow control modeling, transient Stability, MATLAB simulation.

I.INTRODUCTION

In recent years, with the development of electric power systems, transmission systems are becoming increasingly stressed and more difficult to operate. The fast development of solid-state has made flexible AC transmission system (FACTS) devices a promising concept for future power systems. These controllers based on power electronic devices are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady-state conditions. Out of these, The UPFC is the universal and the most versatile FACTS devices, which consists of series and parallel connected converters. It can provide simultaneous and independent control of voltage magnitude and active and reactive power flow. [1] This device is actually a combination of two FACTS device which are STATCOM (Static Synchronous Compensator) and SSSC (Static Series Synchronous Compensator) coupled through a common DC link. SSSC is used to add controlled voltage magnitude and phase angle in series with the line, while shunt converter (STATCOM) is used for voltage regulation at the point of connection, injecting reactive power flow into the line and to balance the real power flow exchanged between the series inverter and the transmission line. [2]

This paper is organized as follows: Section II describes the operating principle of UPFC, its various modes the control also studied. Section III describes the MATLAB simulation results and discussion to validate the performance of the UPFC, STACOM and SSSC for power flow control, the effect of UPFC under fault condition is also presented. Finally Section V describes the conclusion.

II.SYSTEM CONFIGURATION AND THE BASIC OPERATION OF UPFC

A. Model of UPFC

Unified power flow controller is a generalized synchronous voltage source, represented at the fundamental frequency by voltage phasor V with controllable magnitude V $(0 \leq V \leq V_{max})$ and angle α $(0 \leq \alpha \leq 2\pi)$, in series with the transmission line. [3] It has two converters, one connected in series with the line through a series insertion transformer and another connected in parallel with the line through a shunt coupling transformer [4].

Primarily, the series-connected converter is used to inject a controlled voltage in series with the line and thereby to force the power flow to a desired value. In general, the series converter may exchange both real and reactive power while performing this duty. A voltage sourced-converter (VSC) is able to generate the needed reactive power electronically at its AC terminals, but is incapable of handling real power exchange unless there is an appropriate power source connected to its dc terminals. Hence, the series-connected converter has its DC terminals connected to those of the shunt-connected inverter, which performs its primary function by delivering exactly the right amount of real power to meet the real power needs of series converter. It obtains this real power from its connection to the AC bus. The shunt converter can also perform a secondary function by electronically generating reactive power for regulation of the local AC bus voltage. The UPFC thus offers the unique capability of independently regulating the real and reactive power flows on the transmission line, while also regulating the local bus voltage [4]-[5].

The main control parameters of UPFC are voltage magnitude (V), phase angle α and real and reactive power. The control of

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these parameters can be achieved by injecting series voltage with appropriate magnitude and phase angle. The injected voltage is transformed into dq reference frame, which is split into Ed and Eq. These coordinates can be used to control the power flow. The controllers of UPFC for shunt and series branch VSIs are described below [3].

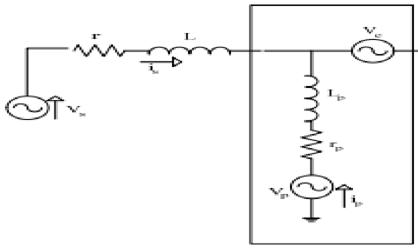


Fig. 1. Equivalent circuit of the UPFC

Applying Kirchhoff law on equivalent circuit shown in Fig.1, the three dynamic equations of the UPFC can be obtained as,

$$\begin{cases} L\frac{di_{s1}}{dt}+ri_{s1}=V_{s1}-V_{c1}-V_{ch1} \\ L\frac{di_{s2}}{dt}+ri_{s2}=V_{s2}-V_{c2}-V_{ch2} \\ L\frac{di_{s3}}{dt}+ri_{s3}=V_{s3}-V_{c3}-V_{ch3} \end{cases} \quad (1)$$

The dynamic equations of the shunt compensator is,

$$\begin{cases} L\frac{di_{p1}}{dt}+r_p i_{p1}=V_{P1}-V_{c1}-V_{ch1} \\ L\frac{di_{p2}}{dt}+ri_{p2}=V_{P2}-V_{c2}-V_{ch2} \\ L\frac{di_{p3}}{dt}+ri_{p3}=V_{P3}-V_{c3}-V_{ch3} \end{cases} \quad (2)$$

The dynamic equations of DC circuit is

$$\frac{1}{2}c\frac{dV_{dc}{}^2}{dt}=P_e-P_{eP}$$

$$P_e=V_{c1}i_{ch1}+V_{c2}i_{ch2}+V_{c3}i_{ch3} \quad (3)$$

$$\mathrm{P_{eP}}=V_{P1}i_{P1}+V_{P2}i_{P2}+V_{P3}i_{P3}$$

Where, Vdc : DC voltage

Pe: Power absorbed by the series compensator and supplied to the common circuit, and Pep: active power provided by the shunt compensator and absorbed by the series compensator

Assuming no active power consumed by capacitors and inverters, the matrix representation of this equations system are:

The matrix representation of the series compensator is,

$$\frac{d}{dt}\begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix}=\begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix}\begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix}+\frac{1}{L}\begin{bmatrix} V_{s1}-V_{c1}-V_{ch1} \\ V_{s2}-V_{c2}-V_{ch2} \\ V_{s3}-V_{c3}-V_{ch3} \end{bmatrix} \quad (4)$$

The matrix representation of the shunt compensator is,

$$\frac{d}{dt}\begin{bmatrix} i_{P1} \\ i_{P2} \\ i_{P3} \end{bmatrix}=\begin{bmatrix} \frac{-r_p}{L} & 0 & 0 \\ 0 & \frac{-r_p}{L} & 0 \\ 0 & 0 & \frac{-r_p}{L} \end{bmatrix}\begin{bmatrix} i_{P1} \\ i_{P2} \\ i_{P3} \end{bmatrix}+\frac{1}{L_P}\begin{bmatrix} V_{P1}-V_{c1}-V_{ch1} \\ V_{P2}-V_{c2}-V_{ch2} \\ V_{P3}-V_{c3}-V_{ch3} \end{bmatrix} \quad (5)$$

Using Park transformation, the two equations (1) and (2), will be written as,

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}=\begin{bmatrix} \frac{-r}{L} & w \\ -w & \frac{-r}{L} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}+\frac{1}{L}\begin{bmatrix} V_{sd}-V_{cd}-V_{chd} \\ V_{sq}-V_{cq}-V_{chq} \end{bmatrix} \quad (6)$$

$$\frac{d}{dt}\begin{bmatrix} i_{Pd} \\ i_{Pq} \end{bmatrix}=\begin{bmatrix} \frac{-r_p}{L} & w \\ -w & \frac{-r_p}{L} \end{bmatrix}\begin{bmatrix} i_{Pd} \\ i_{Pq} \end{bmatrix}+\frac{1}{L}\begin{bmatrix} V_{Pd}-V_{cd}-V_{chd} \\ V_{Pq}-V_{cq}-V_{chq} \end{bmatrix} \quad (7)$$

The dynamic equations of the continuous circuit are:

$$\frac{d_{Vdc}}{dt}=\frac{3}{2CV_{dc}}\left(V_{cd}i_{chd}+V_{cq}i_{chq}\right) \quad (8)$$

Where,

$$i_{chd}=i_{sd}+i_{Pd} \quad (9)$$

$$i_{chq}=i_{sq}+i_{Pq}$$

The generated and absorbed instantaneous active and reactive powers are given below:

The generated active and reactive powers are:

$$P_s=\frac{3}{2}\left(V_{sd}i_{sd}+V_{sq}i_{sq}\right) \quad (10)$$

$$Q_s=\frac{3}{2}\left(V_{sq}i_{sd}-V_{sd}i_{sq}\right) \quad (11)$$

The absorbed active and reactive powers are:

$$P_{ch}=\frac{3}{2}\left(V_{chd}i_{chd}+V_{chq}i_{chq}\right) \quad (12)$$

$$Q_{ch}=\frac{3}{2}\left(V_{chq}i_{chd}-V_{chq}i_{chq}\right) \quad (13)$$

B. Operating Modes of UPFC

The UPFC has many possible operating modes. In particular, the shunt inverter is operating in such a way to inject a controllable current, into the transmission line. This current consists of two components with respect to the line voltage: the real or direct component, which is in phase or in opposite phase with the line voltage, and the reactive or quadrature component, which is in quadrature. The direct component is automatically determined by the requirement to balance the real power of the series inverter. The quadrature component, instead, can be independently set to any desired reference level (inductive or capacitive) within the capability of the inverter, to absorb or generate respectively reactive power from the line. The shunt inverter can be controlled in two different modes [6]-[7]:

1) VAR Control Mode: The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the Var reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage, V_{dc}, is also required.

2) Automatic Voltage Control Mode: The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt coupling transformer. The series inverter controls the magnitude and angle of the voltage injected in series with the line to influence the power flow on the line.

3) Direct Voltage Injection Mode: The reference inputs are directly the magnitude and phase angle of the series voltage.

4) Phase Angle Shifter Emulation mode: The reference input is phase displacement between the sending end voltage and the receiving end voltage.

5) Line Impedance Emulation mode: The reference input is an impedance value to insert in series with the line impedance

6) Automatic Power Flow Control Mode: The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

C. UPFC based control system

In UPFC the shunt converter operates as a STATCOM, and it controls the AC voltage at its terminal as well as at the DC bus. It works on a dual voltage regulation loop. A UPFC the two degree of freedom are used to control the active and reactive power. The series converter operates on either Power flow control (automatic control mode) or in manual voltage injection mode [8]. In order to understand the UPFC Control System the phasor diagram is shown in fig 2.

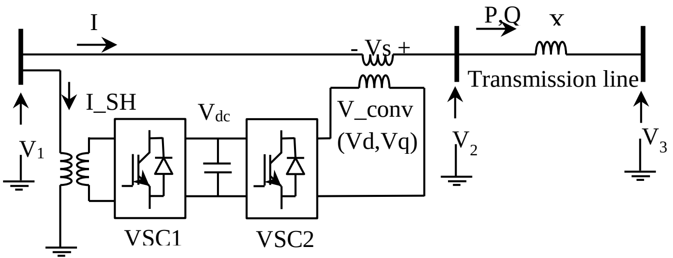


Fig. 2. Single-line Diagram of a UPFC

$$P = \frac{V_2 V_3 \sin\delta}{X} \tag{14}$$

$$Q = \frac{V_2(V_2 - 3\cos\delta)}{X} \tag{15}$$

In power control mode, the measured active power and reactive power are compared with reference values to produce P and Q errors. The error P and error Q are then given to two voltage regulator to compute the Vd and Vq component of the voltage to be synthesized by the VSC. (Vq in quadrature with V1 control active power and Vd in phase with V1 controls reactive power). In manual voltage injection mode the regulators are not used. The reference value of injected voltage Vdref and Vqref are used to synthesize the converter voltage [5].

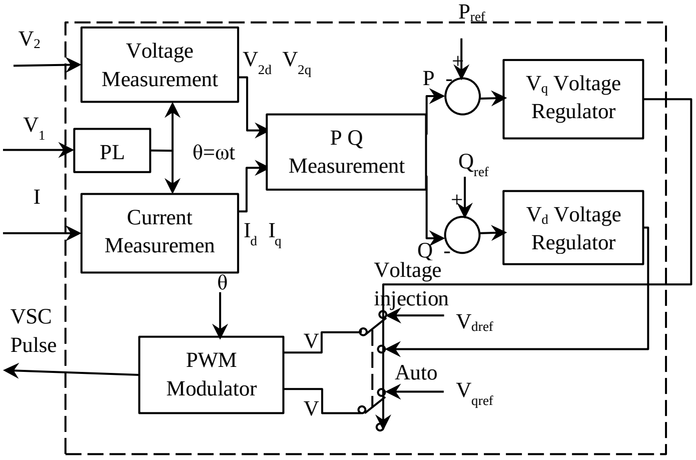


Fig. 3. Simplified Block of the Series Converter Control System [9]

D. The effect of UPFC on power system

UPFC can achieve the target of control the active and reactive power on transmission line, and the active power PSE exchanged between the series part of UPFC and system must be provide by the parallel part of UPFC which can absorb power from the transmission line [10].

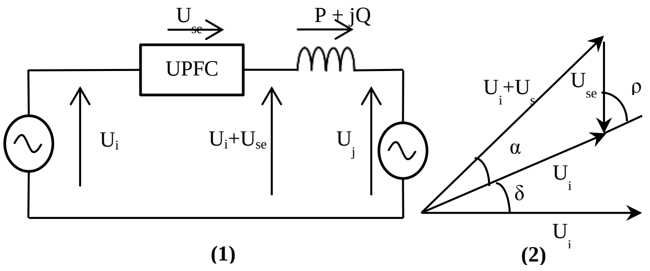


Fig. 4. two-machine system with UPFC (1) equivalent circuit (2) vector relations

From the Fig.4, we can see that: the ending power of the line can be expressed as:

$$P - jQ = U_1\left(\frac{U_1 + U_{se} - U_2}{JX}\right) \tag{16}$$

Suppose if the UPFC is installed at the end of transmission line, according to the vector relations, we can get the active and reactive power equations as follows:

$$P = \frac{U_1 U_2}{X} sin\,\delta + \frac{U_{se} U_2}{X} sin(\,\delta + \rho) \qquad (17)$$

$$Q = \frac{U_1 U_2}{X} cos(\delta - 1) + \frac{U_{se} U_2}{X} cos(\delta + \rho) \qquad (18)$$

It can be seen from the above equation that when ρ = 90°-δ, transmission line which the UPFC is installed can obtain the greatest power, that is to say, at this point Use has the greatest impact on power flow of the line. Make an appropriate transformation of equation (17) and (18), we can obtain the reactive power and active power equation as follows:

$$\left(P - \frac{U_i U_j}{X}\sin\delta\right)^2 + \left[Q - \frac{U_i U_j}{X}(\cos\delta - 1)\right]^2 = \left(\frac{U_{se} U_j}{X}\right)^2 \qquad (19)$$

Take different values of δ, the reactive power and active power curve that on the terminal of the transmission line is shown in Fig.6

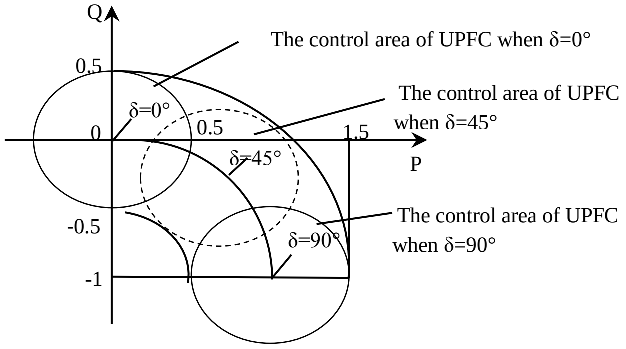


Fig. 5. Reactive power and active power curve when δ is different

From the above we can see that UPFC devices can expands the operating range of the transmission system greatly. especially when δ = 90°, transmission system has reached the limit point of stable operation if there is no compensation of UPFC devices, Operation range of the system is far beyond the original range, and the system can still running stability after the UPFC device inputted in the system. It is important to optimal operation for the system, improve the stability limit of the system and improve system stability margin if appropriate number of UPFC devices are installed in a system [10].

III. ILLUSTRATIVE EXAMPLE

In order to evaluate the dynamic performance of UPFC a simple power systems 500 kV was tested (Fig.6), simulation tests have been carried out by MATLAB SIMULINK software in following conditions:

- Scenario A: UPFC operation in STATCOM Var control mode
- Scenario B: UPFC operation in SSSC power flow control mode
- Scenario C: UPFC operation in power flow control mode
- Scenario D: effect of UPFC on system performance under fault condition (i.e. single line to ground fault)

For our case, we used a simple power systems 500 kV including 4 buses (B1 to B4) connected through three-phase lines L1, L2 and L3. System has being supplied by three 500 kV infinite buses. UPFC is located buses B1 and B2, and is used to control active and reactive power of 500 kV buses as well as UPFC bus.

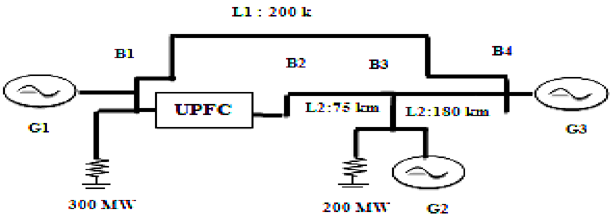
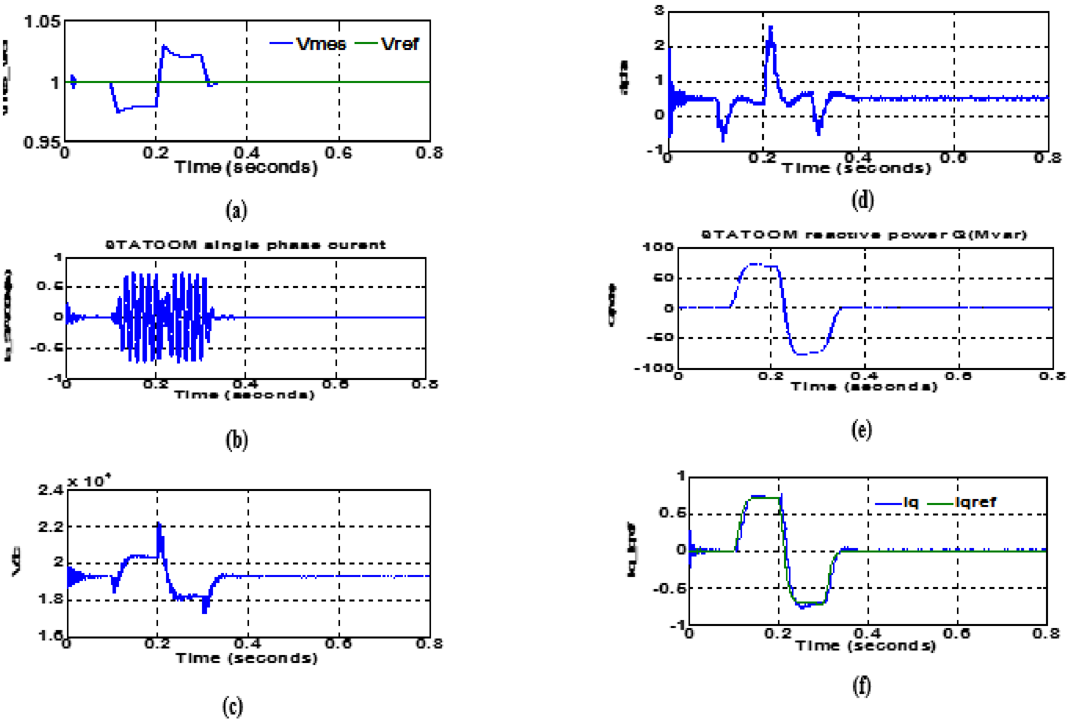


Fig. 6. Single line diagram for proposed test system

Scenario A: Dynamic response of the STATCOM

To study the performance of the UPFC in STATCOM Var control mode, the reactive power reference is set to + 0.7 pu (+70MW) at t = 0.1 s and -0.72pu (-72 Mvar) at t = 0.2 s. Finally, at t=0.3 s the source voltage in set back to its nominal value and the STATCOM operating point comes back to zero Mvar. Initially the AC reference voltage is programmed to transiently change from 1 pu to 0.955 pu, from 0.955 pu to 1.045 pu, and from 1.0491 pu to1 pu (as shown in Figure 7.a) causing the STATCOM operating point to change from fully capacitive to fully inductive mode. The simulation results are shown in Figure 7.

For an AC reference voltage equals to 1 pu, the initial STATCOM converter current is zero (zero current) as shown in Figure 7.b.



(a) (b) (c) (d) (e) (f)

figure 7: waveforms indicates Performance of the system with STATCOM

Then, at t=0.2 s the source voltage is increased to1.045 pu of its nominal value. The VSC reacts by changing its operating point from capacitive modes to inductive modes in order to keep voltage at 1.021 pu as seen in Figure 7.e. At this point the STATCOM absorbs 72 Mvar. Also it's clear that the DC voltage has been lowered to 18.2 kV (as shown in Figure 7.c).

The DC voltage side is 19.3 kV as shown in Figure 7.c. At steady state, the phase shift angle (δ) is very close to zero, as there is no active power circulating from the STATCOM converter (as shown in Figure 7.d). At t=0.1s, for an AC voltage decreased by 4.5 % (0.955 pu of nominal voltage) .The VSC reacts by generating reactive power (Q=+70 Mvar) in order to keep voltage at the connection bus at 0.979 pu(as shown in Figure 7.e).

At this point, it is necessary to increase the DC voltage which is achieved by the current regulator control; the DC voltage has been increased to 20.4 kV (as shown in Figure 7.c). The phase shift angle (δ) becomes transiently negative (Figure 7.d), the capacitor is smoothly charged without causing oscillations in the control variables.

The phase shift angle (δ) becomes transiently positive (Figure 7.d) discharging the DC capacitor. Finally, at t=0.3 s, the system returns to its steady state operation because there is no reactive power exchange and the STATCOM follows the reference value. From Figure 7, it is clear that the STATCOM responds to the variation of the reactive power and it can change very quickly and smoothly.

Scenario B: *UPFC operation in SSSC*

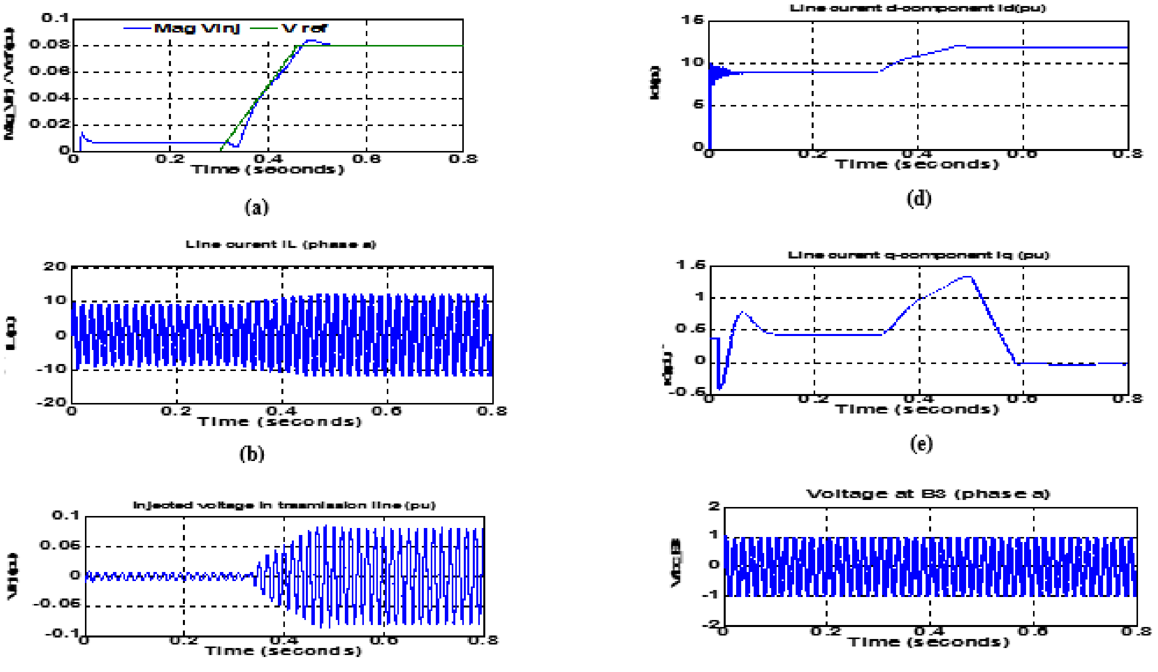
To study the performance of the UPFC in SSSC power flow control mode, the active and reactive power reference is set to 8.7 and -0.6 pu respectively. Then, at t = 0.25 s and t = 0.5 s, the active and reactive power reference are increased to 10pu and +0.7 pu respectively. The simulation results are shown in Figure 8.

The initial reference values of active and reactive power are equal to 8.7 and -0.6 pu., resulting in a series voltage close to zero, as seen in Figure 8.a. The purpose is to increase the transmission capacity of the line as well as to reduce the reactive power generation by the receiving bus.

At t = 0.25 s and t = 0.5s the step changes are applied, there are changes in amplitude and the angle of the line current, by means of the insertion of the series voltage (shown in Figure 8.b). Looking closer to Fig.8 at t=0.5s it is noticed that the injected series voltage decreases after the step change in the reactive power is applied.

Fig. 8.d, Fig. 8.e shows the change in d and q component of line current according to step changes in active and reactive power respectively. Figure 8.f shows the receiving end voltage at bus B3 is kept constant throughout the whole simulation.

From Figure 8, the operation of the UPFC in SSSC effectively controls the transmitted active and reactive power.



(a) (d)

(b) (e)

(c) (f)

Figure 8: indicates the network operational trends with SSSC (a) magnitude and reference voltage (b) Iabc current (c) voltage injection (d,e) d and q component of line current (f) voltage at bus B3

Scenario C: *UPFC operation in power flow control mode*

In this experiment we use an UPFC to control active and reactive power of 500 kV buses as well as UPFC bus.

Initially, the natural power flow through bus B2 when zero voltage is generated by the series converter is P=+870 MW (8.7pu) and Q=-60 Mvar (-0.6pu) is taken as a reference.

Form Fig. 9, we can observe that after a transient period lasting approximately 0.15 sec, the steady state is reached (P=+8.7 pu; Q=-0.6 pu). Then At t=0.25 sec Pref is changed to +10 pu (+1000MW) and at t=0.5 sec, Qref is changed to +0.7 pu (+70 Mvar). Waveforms are reproduced in figure 9.

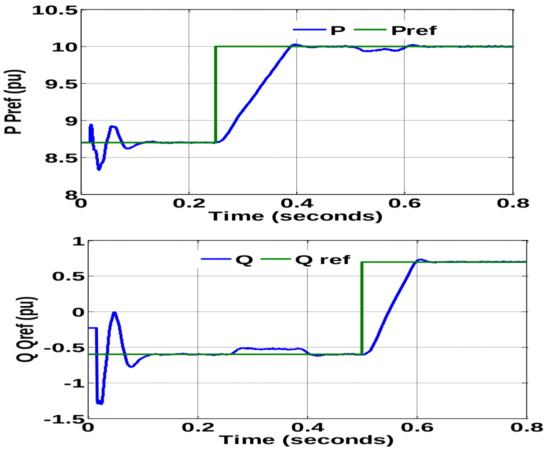


Fig.9. UPFC responses for changing active power at 0.25sec and reactive power at 0.5 sec

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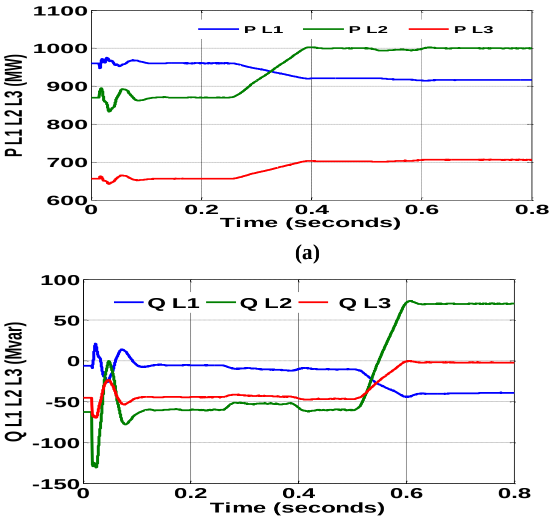

(a)

(b)

Fig.10. a) Line active power flow and b) reactive power flow

From the Fig. 10, we observe the resulting changes in P Q on the three transmission lines, The reference voltage of the shunt converter will be kept constant at Vref=1 pu during the whole simulation.

The simulation results are shown in Fig. 10 Steady state is reached (P=+8.7 pu; Q=-0.6 pu (as shown in Fig.8.a), then, at t = 0.2 s the active power is smoothly ramped to the new setting (+ 10 pu) in approximately 150 ms.. As a result, the transmitted power in transmission L2 is ramped from its steady state (8.7 pu) to the new state (10 pu) and the transmitted power in transmission line L1 is reduced to 9 pu(as shown in Fig. 10.a).

At t = 0.5 s, the reactive power is increased to its new setting (+0.7 pu) very quickly .As a result, the reactive power in transmission line L2 is increased from its steady state value to the new value while the reactive power in transmission line L1 is decreased to about -0.5 pu (as shown in Fig. 10.b).

This control of the reactive power is obtained by varying the magnitude of the secondary voltage Vs generated by the shunt converter while keeping it in phase with the bus B1 voltage Vp as shown in “Fig. 11,” that Vs started to appear at t = 0.5 sec due to changing the value of the reactive power.

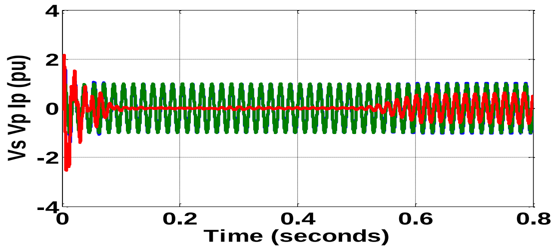

Fig.11. Series & Parallel injected voltages

Also it can be seen from “Fig. 12,” that the Vdc increases from 17.5 kV to 21 kV due to the increasing of the reactive power, causing the STATCOM operating point to change from fully inductive to fully capacitive mode

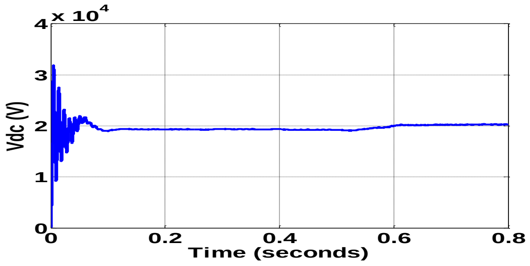

Fig.12. DC Link capacitor voltage

Scenario D: effect of UPFC on system performance under fault condition (i.e. single line to ground fault)

The performance of UPFC is analyzed by applying fault: Suppose that single phase to ground short circuit fault occurs at the bus 2(Line 2), Doing transient simulation on this system, single phase to ground short circuit fault occurs at bus 2, during 0.6s to 0.61s, at 0.61s the fault is removed, then maintain the single-loop operation.

Form Fig.13 we can observe that when the fault is applied (short-circuit) so this fault will cause the oscillation on active and reactive power flow of the lines, we can see clearly that the system oscillation is more important and dangerous without UPFC as shown in Fig.13.a (it can reach 3000 MW and 2500 MVar), while the oscillation with the UPFC is less important (it can reach 1300 MW and 500 MVar), the system power can restore stability after some sec running when the fault removed, active and reactive power of the system still shocking seriously in a long time after the fault removed when UPFC does not work

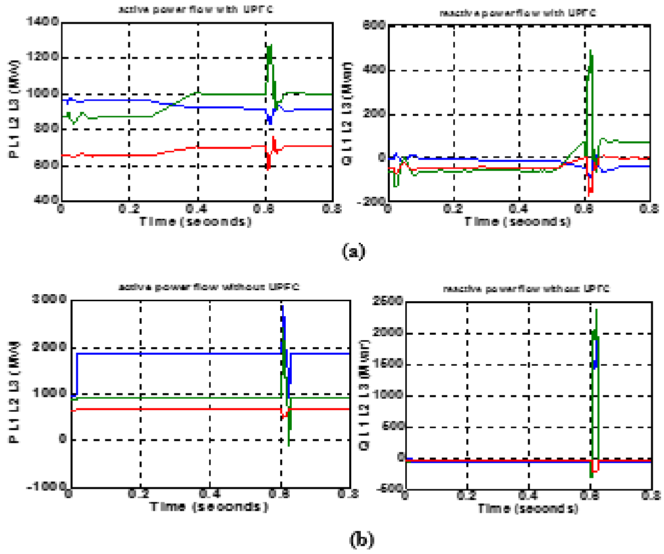

Fig.13. Active and reactive power wave form as a result of Single L-G fault is applied at line 2 of the test system (a)with and (b)without the UPFC

Also it can be seen from Fig.14 that, capacitor voltage starts decreasing as fault occurs. At 0.61 sec fault is cleared and V_{dc} still shocking seriously in some time after the fault removed, capacitor starts charging and becomes constant.

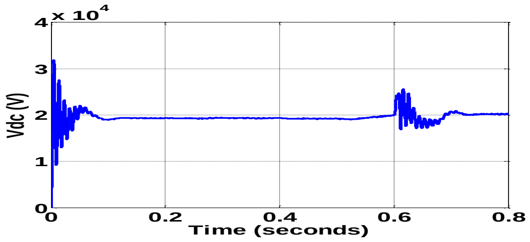

Fig.14. DC link capacitor voltage of UPFC under fault applied at t= 0.6 sec

V. CONCLUSION :

In this study, the Matlab/Simulink environment is used to simulate a simple grid with UPFC, and again by using STATCOM and SSSC, the test system was analyzed also with and without incorporating UPFC under fault to examine the performance dynamic of UPFC in transmission line. According to what mentioned in the simulation results obtained obtained by introducing UPFC into transmission system provide better result as compared to the result obtain by using SSSC and STATCOM into the transmission system, this given an indication that UPFC have the capability to improve the voltage profile, as well as regulating the active and reactive power of the buses and the lines even during the fault conditions without losing balance and improve the stability of power system.

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