Simulation and Analysis of Unified Power Flow Controller Using SIMULINK

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Abstract—**The fast development of power electronics technology has given birth of new devices, which are very useful in improving the power system performances. The name given to these devices is flexible AC transmission system (FACTS) controllers. The unified power flow controller is the most effective and versatile FACTS device. This paper presents simulation and analysis of UPFC controller based on d-q axis theory, which includes series controller, shunt controller and DC bus voltage controller. The effects of different controllers along with impedance of series transformer and transmission line charging are investigated through control block model in SIMULINK. The effectiveness of the proposed approach is demonstrated through different case studies.**

Index Terms—**FACTS, UPFC controllers, d-q axis control, SIMULINK**

I. INTRODUCTION

Opening of competition in electricity supply industry has created a new scenario in terms of power flow patterns and therefore problems of transmission line capacity arise. High power semiconductor devices with fast control features have made possible to control the power flow more efficiently and effectively. This is achieved by employing flexible ac transmission systems (FACTS) controllers which are able to enhance power transmission capability, increase line loading up to thermal limits without compromising system security and reliability. In addition, these can also facilitate the reduced power flows in heavily loaded lines resulting in increase loadability, low system loss, improved stability of system and reduced cost of production.

Due to environmental, cost and right-of-way problems transmission lines are forced to operate to its maximum limit, which threatens the grid stability and cascade outages. Under these circumstances, the use of FACTS controllers is essential wherever economically feasible. This is only possible due to development of high power semiconductor device with fast control at reasonable cost. There are several FACTS controllers; namely, static var compensator (SVC), thyristor controlled series compensator (TCSC), thyristor controlled phase angle regulator (TCPAR), static compensator (STATCOM), unified power flow controller (UPFC) etc. [1-3].

A unified power flow controller (UPFC) is the most effective and versatile FACTS device capable of controlling instantaneous power flow and provides dynamic control of system parameters (voltage, line impedance, and phase angle) independently or simultaneously in appropriate combinations. The UPFC consists of a combination of a shunt and series branches. The real and reactive power flows in the transmission line can be regulated by changing the magnitude and phase angle of series injected voltage produced by series converter. The shunt connected converter provides the real power drawn by series branch and the losses therein. In addition, it can independently provide reactive power compensation to the system by controlling the reactive current.

To simplify the control analysis, to improve the dynamic performance and to reduce the interaction between real and reactive power flow of UPFC, d-q axis control strategies have been proposed [4-6]. The performance of UPFC with different controllers has been evaluated through simulation and experimental verifications [7]. These are PI controller, decoupled PI (PI-D) controller, cross-coupling controller, and robust H_∞ controller. It is reported [7] that the decoupling controller has shown excellent performance when parameters of power transmission are known. The cross-coupling and robust H_∞ controllers show good dynamic performance. These controllers are more robust than PI-D controller with consideration of uncertainties and variations in transmission line parameters. But above references have not considered the effect of impedance of series transformer, transmission line charging and source impedance.

This paper presents the comprehensive model of UPFC controllers in SIMULINK block set to investigate the effect of series impedance of the transformer and charging of the transmission line based on d-q axis decoupled model. The d-q control theory for UPFC is developed which includes series controller, shunt controller and DC bus voltage controller. The decoupling of the active and reactive current controllers is incorporated. The dynamic model of UPFC is derived in the d-q (synchronously rotating at the system angular frequency, ω) frame of reference and followed by PI control strategy for active and reactive power control. The effects of other controllers are also examined through simulation studies. The results are obtained for different case studies, which include step changes in active and reactive power flow and response for pulse disturbances in sending end voltage magnitude.

II. UNIFIED POWER FLOW CONTROLLER

The rapid development of the power electronic devices has made feasible the control of power flow in a power system without generation rescheduling. The UPFC is most versatile FACTS controller capable of instantaneous power flow control. UPFC provides dynamic control of transmission

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parameters such as voltage, line impedance and phase angle simultaneously [1-3].

The UPFC consist of two voltage source converters as shown in Fig. 1. The first converter (shunt converter) known as STATCOM (static synchronous compensator) injects an almost sinusoidal current of variable magnitude, at the point of connection. The second converter (series converter), known as SSSC (static synchronous series compensator) provides the main functionality of the UPFC by injecting an AC voltage V_{se}, with a controllable voltage magnitude ($0 \leq V_{se} \leq V_{se}^{\max}$) and phase angle Φ_{se} ($0 \leq \Phi_{se} \leq 360^0$) at the power frequency, in series with line via a series transformer. This injected voltage can be considered essentially as a synchronous AC voltage source. The line current flows through this voltage source resulting in real and reactive power exchange between it and the AC system. The real power exchanged at the AC terminal (i.e., at the terminal of series transformer) is converted by the inverter into DC power which appears at the DC link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the converter.

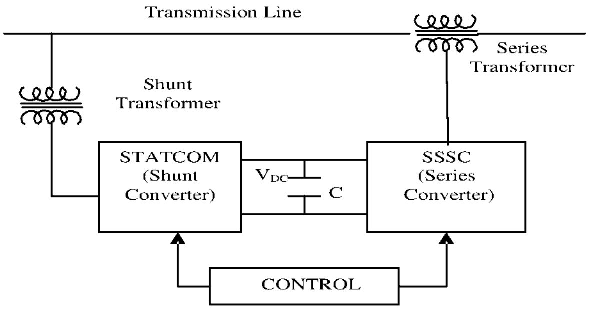

Fig. 1. Basic Circuit diagram of UPFC

The basic function of shunt converter is to supply or absorb the real power demanded by series converter at the common DC link. Shunt converter can also generate or absorb controllable reactive power, if it is desired, and thereby it can provide independent shunt reactive compensation for the line. The real and reactive power flows in the transmission line are influenced by both the amplitude and phase angle of the series compensating voltage. To get the independent control of real and reactive power flow in the line proper design of real and reactive power controllers is necessary.

III. MODELING OF UPFC IN d-q FRAME OF REFERENCE

The equivalent circuit of a UPFC connected in a line is shown in Fig.2. A 220 KV, 100 MVA line is considered for study. The system parameters are given in Appendix. The series and shunt converters are represented by controllable voltage sources V_{se} and V_{sh} respectively. R_s and L_s are source resistance and inductance respectively; R_r and L_r are transmission line resistance and inductance respectively. R_{sh} and L_{sh} represent the resistance and leakage inductance of the shunt transformer, respectively. R_{se} and L_{se} represent the resistance and leakage inductance of the series transformer, respectively. Performing standard d-q transformation [4-6] of the current through the shunt transformer and series transformer derives the dynamic model of UPFC. Here synchronous reference frame is considered for transformation and quantities are represented in per unit system.

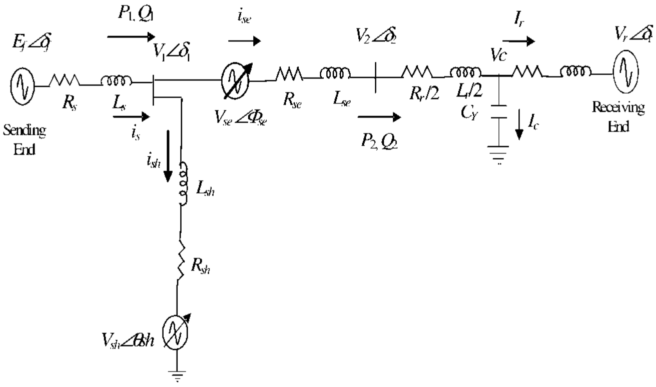

Fig. 2. Single line diagram of UPFC connected in a power system

A. Shunt Converter

From Fig. 2, dynamic equations of the shunt part of UPFC can be written as

$$\frac{di_{shd}}{dt} = -i_{shd}\frac{R_{sh}}{X_{sh}}\omega_{Base} + \omega_{Base}\, i_{shq} + \frac{\omega_{Base}}{X_{sh}}(V_{1d} - V_{shd}) \qquad (1)$$

$$\frac{di_{shq}}{dt} = -i_{shq}\frac{R_{sh}}{X_{sh}}\omega_{Base} - \omega_{Base}\, i_{shd} + \frac{\omega_{Base}}{X_{sh}}(V_{1q} - V_{shq}) \qquad (2)$$

where the quantities with subscript d and q are d-axis and q-axis quantities, respectively. Time t is in seconds and ω_{Base} is base frequency in rad/sec. All other quantities are in per unit system.

B. Series Converter

From Fig. 2, a mathematical model of the transmission system including the series part of UPFC can be derived and is given by equations

$$\begin{aligned}\frac{di_{sed}}{dt} = -i_{sed}\frac{R_{se}}{X_{se}}\omega_{Base} + \omega_{Base}\, i_{seq} + \\ \frac{\omega_{Base}}{X_{se}}(V_{1d} + V_{sed} - V_{2d})\end{aligned} \qquad (3)$$

$$\begin{aligned}\frac{di_{seq}}{dt} = -i_{seq}\frac{R_{se}}{X_{se}}\omega_{Base} - \omega_{Base}\, i_{sed} + \\ \frac{\omega_{Base}}{X_{se}}(V_{1q} + V_{seq} - V_{2q})\end{aligned} \qquad (4)$$

C. Converter DC Side Voltage Controller Design

Net power input (real power in shunt branch minus real power flows into series branch) to UPFC should instantaneously meet the charging rate of capacitor (C) and losses in the UPFC system. The mathematical equations can be derived and written as follows:

$$P_{sh} - P_{se} = V_{dc}\left[C\frac{dV_{dc}}{d\theta} + g_c V_{dc}\right] \qquad (5)$$

$$V_{dc}\left[C\frac{dV_{dc}}{d\theta} + g_c V_{dc}\right] = V_{shd}i_{shd} + V_{shq}i_{shq} - V_{sed}i_{sed} - V_{seq}i_{seq} \qquad (6)$$

where $\theta = \omega_{Base}\, t$

$$\frac{dV_{dc}}{dt} = -\frac{g_c \omega_{Base}}{b_c} V_{dc} + \frac{\omega_{Base}}{b_c V_{dc}} \Big[V_{shd}\, i_{shd} + V_{shq}\, i_{shq} - V_{sed}\, i_{sed} - V_{seq}\, i_{seq} \Big] \tag{7}$$

The dynamic behavior of the dc-capacitor voltage can be realized by (7), where b_c is susceptance and g_c is the conductance of the capacitor, respectively. DC voltage level is controlled by the shunt converter, which adjusts the amount of real power flow from the AC system into the common dc link.

IV. CONTROL STRATEGY FOR UPFC

The main function of UPFC is to control the real and reactive power flows in the line along with the bus voltage control for achieving the desired objectives. Ignoring the non-linearities and saturation of transformer, the voltage and current quantities can be transformed into the d-q reference frame quantities (synchronously rotating q-axis is in phase with A-axis at t=0) as shown in Fig. 3. Since UPFC has two converters, their controllers are described separately. The real and reactive power flow in the line can be controlled independently using the series injected voltage. The shunt inverter injects a controlled shunt current (indirectly) by varying the shunt converter voltage. This converter is responsible for ac-bus and dc-link voltage control (indirectly).

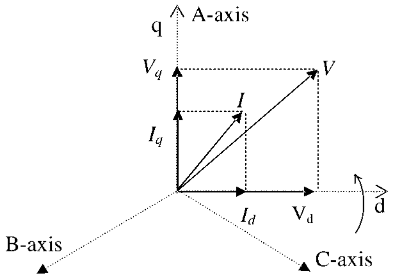

Fig. 3. Definition of orthogonal co-ordinates

A. Series Converter Control

The realization of power flow control is done by using two PI controllers, as shown in Fig. 4, which control the series injected voltages (V_{sed}, V_{seq}). The reference line currents are calculated by reference values of active and reactive power flow in the transmission line at node 2 as

$$i_{sed}^{ref} = \frac{2}{3}\frac{P_{ref}V_{2d} - Q_{ref}V_{2q}}{V_2^2} \tag{8}$$

$$i_{seq}^{ref} = \frac{2}{3}\frac{P_{ref}V_{2q} + Q_{ref}V_{2d}}{V_2^2} \tag{9}$$

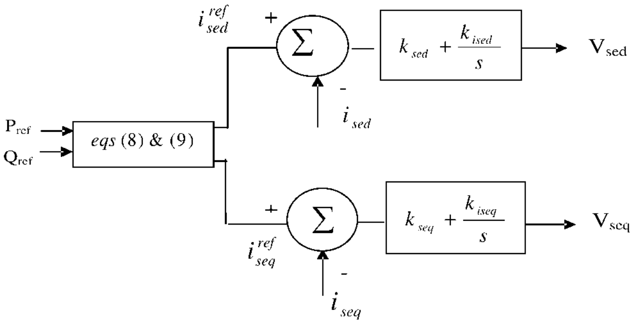

Fig. 4. Series Converter Control Structure

B. Shunt Converter Control

The control strategy of shunt converter concerns with the control of AC bus and DC link voltage is shown in Fig. 5. Currents in d-q frame (i_{shd} ,i_{shq}) are transformed into d'-q' frame to coincide d'-axis with AC bus-1 voltage (V_1). The voltage at bus -1 is controlled by reactive power injection at bus-1. Hence the q'-axis component of current controls the voltage magnitude V_1. Also the DC link voltage depends on the real power flow from bus-1 to the shunt converter and therefore controls, I'_d. AC bus voltage regulator determines the reference for reactive component (i.e. q' component). DC link Voltage regulator determines the real component (d') of shunt current.

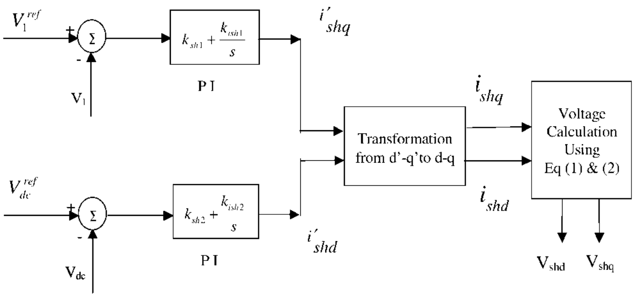

Fig. 5. Shunt converter control structure for UPFC

The currents in d'-q' frame of reference i'_{shd} and i'_{shq} are related to d-q axis currents as below. (Using Fig. 6)

$$i'_{shd} = i_{shd}\cos\delta + i_{shq}\sin\delta \tag{10}$$

$$i'_{shq} = -i_{shd}\sin\delta + i_{shq}\cos\delta \tag{11}$$

Similarly, the voltages in d'-q' frame of reference can be determined using Fig. 6.

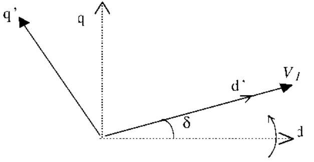

Fig. 6. Relation between dq and d'q' frame of references

V. SIMULINK MODELS

For the performance evaluation of control strategy, simulation is carried out in SIMULINK block set of MATLAB. Models for transmission line, shunt control, series control and DC voltage control are developed separately. The combined UPFC model is shown in Fig. 7. SIMULINK models of each block are shown in Figs. 8-13. Measuring sensing delay circuits are introduced in Fig. 10 and Fig. 12 to avoid numerical looping.

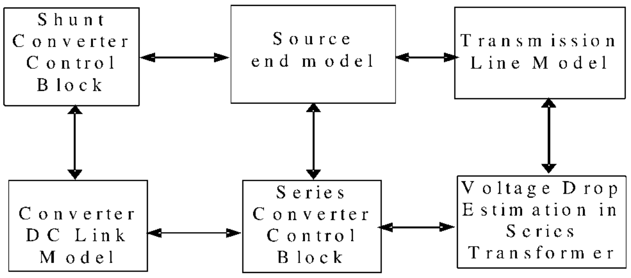

Fig. 7. Complete UPFC model

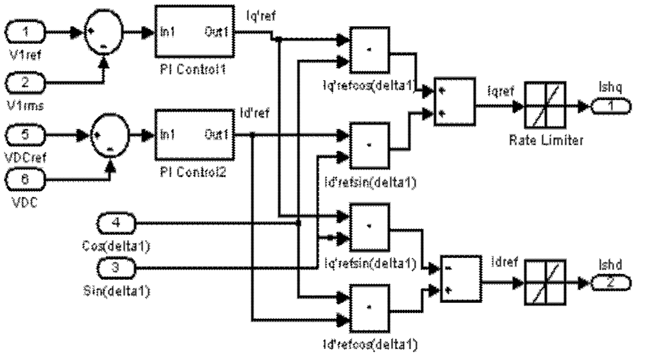

Fig. 8. Shunt Converter Control Block

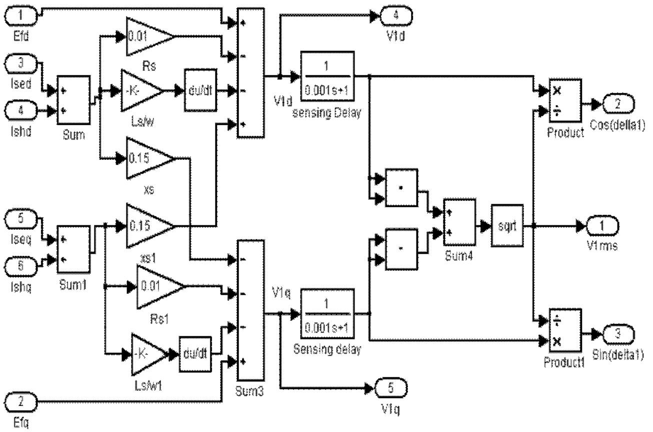

Fig. 9. Source end model

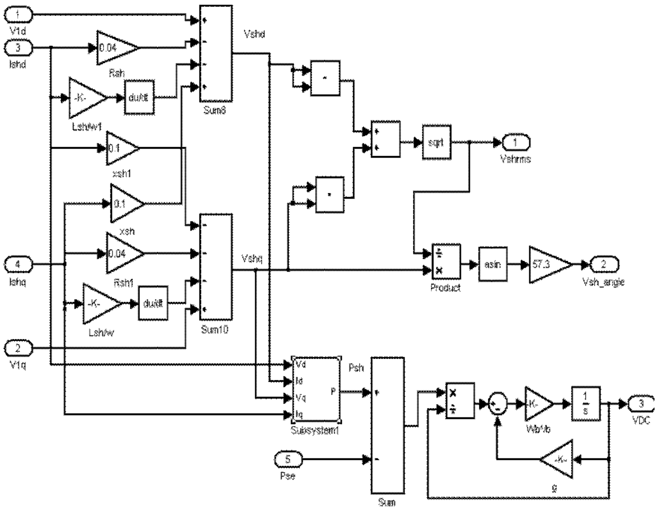

Fig. 10. DC Link model

VI. SIMULATION RESULTS

The active and reactive powers at the UPFC terminal towards the transmission line i.e. P_2 and Q_2 (as shown in Fig. 2) are controlled to desired real and reactive power flows (P_{ref} and Q_{ref}). At the initial state, the receiving end voltage, active and reactive powers are specified for the power system. The reference currents i_{sed}^{ref} and i_{seq}^{ref} are computed from (8) and (9). The reference voltages, V_1^{ref} and V_{dc}^{ref}, are equal to their respective steady state values. Different controllers such as PID, H_∞ etc were also tried and it was found that PI controllers are giving the better results in terms of settling time and peak overshoot. Therefore the results with PI controllers are only presented in this paper.

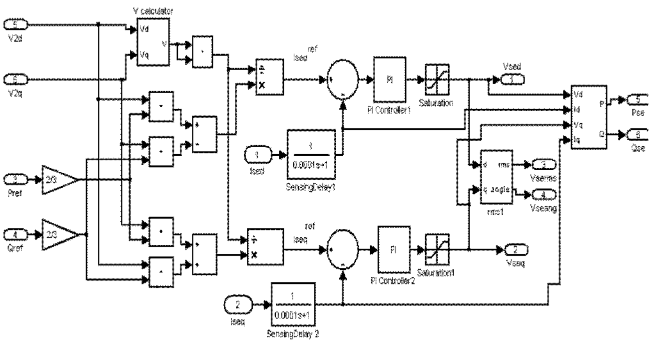

Fig. 11. Series converter control

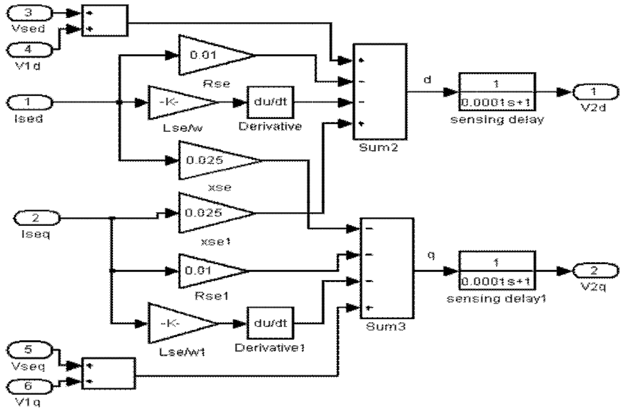

Fig. 12. Voltage drop estimation in series transformer

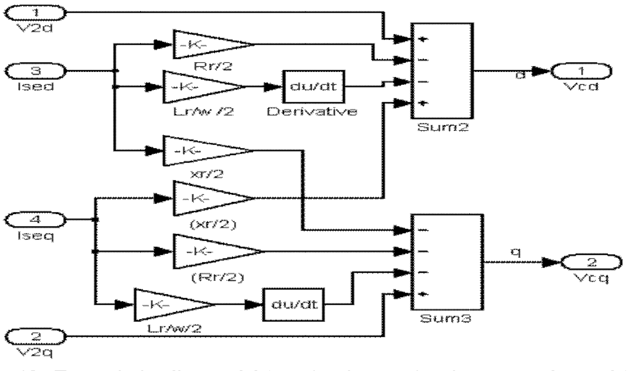

Fig. 13. Transmission line model (part 1-voltage estimation at capacitor node)

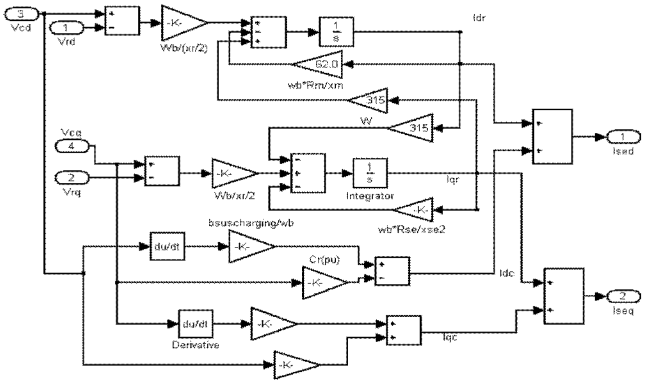

Fig. 14. Transmission line model (part 2- line current calculation)

The T- model of line representation has been used. π-model of transmission line was also considered and found that the effect of capacitor at the UPFC terminal make the control to destabilize. Since the capacitance effect is distributed though out the line, T-representation was found suitable and simulation was performed. The system parameters and control system parameters are given in Appendix. To demonstrate the effectiveness of the proposed model along with controllers, various case studies are simulated.

Case-A:

In this case it was assumed that there is no power flow ($E_f=1\angle 0$ and $V_r=1\angle 0$) and initial parameters setting of UPFC are zero i.e. series injected voltage and injected reactive power current are zero which can be seen from Fig. 15. This is the case when generator is connected to the infinite bus having equal voltage magnitude angle. After achieving the steady state, the reference settings in active and reactive power flow are changed to 0.5 pu and 0.4 pu at 0.03 sec. The case study is done for step changes in active and reactive power flow. It can be seen that real and reactive power get settled to desired values in one and half to two cycles. The variation of real and reactive power flow, sending end voltage magnitude, dc link voltage, series injected voltage magnitudes and angles, and shunt voltage magnitude and angles are shown in Figs. 15(a) to 15(h).

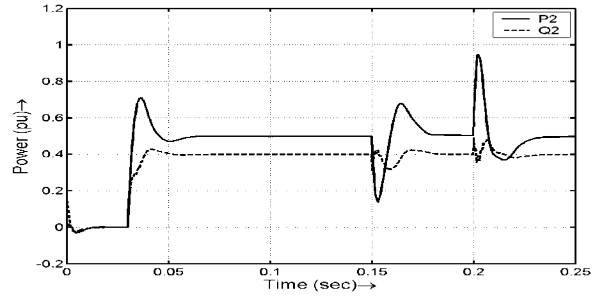

Fig 15(a): Power flow (case-A&B)

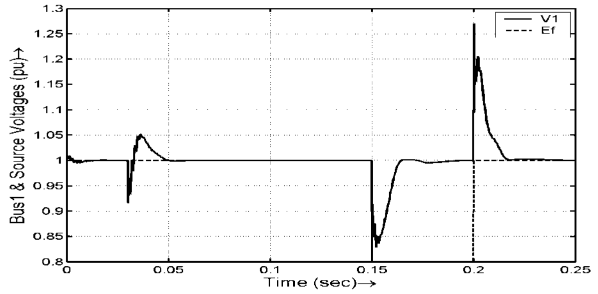

Fig 15(b): Voltage magnitude at bus-1 (case-A&B)

Case-B:

A pulse disturbance in sending end voltage (E_f) is applied at time 0.15 sec. The voltage magnitude was changed to 0.9 pu from 1.0 pu at t= 0.15 s and then back to 1.0 pu at t =0.2s. The real and reactive powers are settled to desired values in one to two cycles. Due to limited space, the results of Case-A and case-b are plotted on the same figures for different parameters of UPFC and systems. The dynamic regulation of both power and bus voltages are shown in Fig. 15 in continuation to case A (from t=0.15s onwards).

The variation of P_2 (solid line) and Q_2 (broken line) with respect to time (sec) is shown in Fig. 15(a). Voltage at bus-1 (V_1) and sending end voltage E_f are plotted together in Fig. 15(b) for comparison purpose. DC link capacitor voltage is plotted in Fig. 15(c). Variation of series and shunt injected voltage (magnitude) can be seen from Fig. 15(d). Shunt voltage magnitude has some transient at the beginning but settles down quickly. Fig. 15(e) presents the plot of angles of series injected voltage and shunt injected voltage. Fig. 15(f) presents the phase angles of voltages at node 1 and 2.

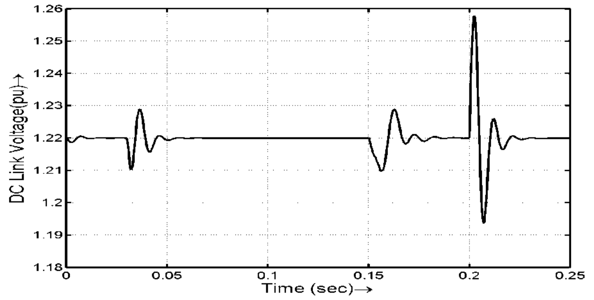

Fig 15(c): DC link capacitor voltage (case-A&B)

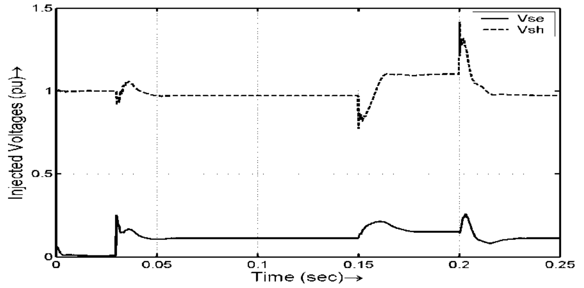

Fig 15(d): Series and shunt injected voltage magnitude (case-A&B)

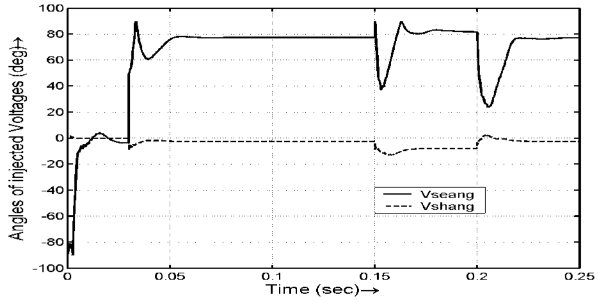

Fig 15(e): Angles of injected voltages (case-A&B)

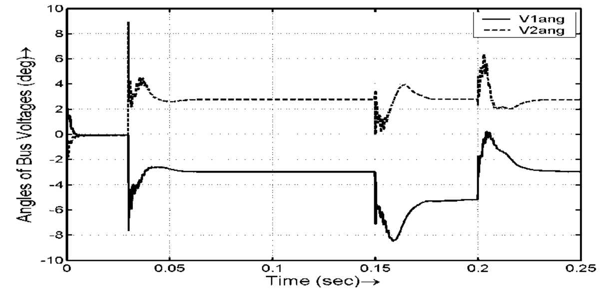

Fig. 15(f): Angles of bus voltages of UPFC (case-A&B)

Case-C:

To see the effect of series transformer impedance and line charging, the simulation was also performed without these. The complete simulation results are not shown due to limited space. It was observed for the same condition as of Case-A that the peak overshoots for real power (P_2) is 0.8 pu whereas it is 0.7 pu in the case of Case-A and of the reactive power (Q_2) it is the same as the Case-A. The magnitudes of series injected voltage and shunt voltage are very close during the steady state. The voltage angles during the transient are quite different as compared to Case-A (Fig. 15(f)), which can be seen from Fig. 16.

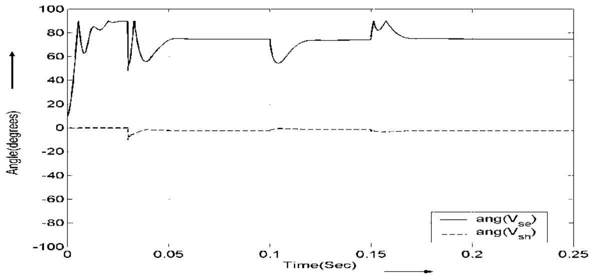

Fig. 16: UPFC series and shunt voltage angles (case-C)

Case-D:

In this case the effect of series transformer impedance and line charging are considered but the voltage angle of generator internal voltage (E_f) is taken as $1\angle 10^0$ and initial parameters setting of UPFC are fixed so that there is no power flow in the line (power blocking case). After achieving the steady state, the reference settings in active and reactive power flows are changed to 0.5 pu at 0.05 sec. It was found that the real and reactive powers are achieved to the reference setting at t =0.08s with same overshoot as Case-A. Variations of series injected voltage magnitude and shunt voltage magnitude have some spikes at beginning and finally settles which can be seen from Figs. 17(a) and 17(b). Fig. 17(c) presents the plot of angle of series and shunt voltages.

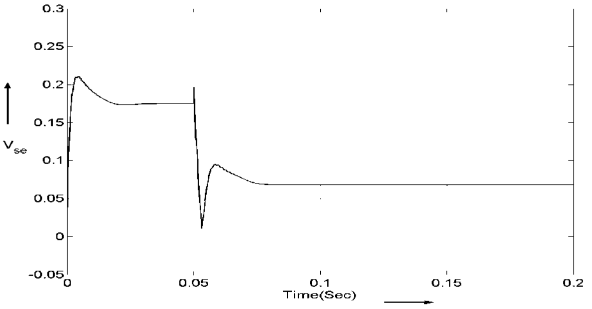

Fig 17(a): Series injected voltage magnitude

VII. Conclusion

SIMULINK model for complete UPFC is developed using d-q control theory, which includes series controller, shunt controller and DC bus voltage controller. Series transformer impedance, transmission line charging and source impedance are considered in the simulation. The PI control scheme is used for the developed control block models. The developed models are very general and can be used for several case studies which are useful for several design purposes. The simulation results of some of the cases are presented. It is found that the PI controller has good regulating properties.

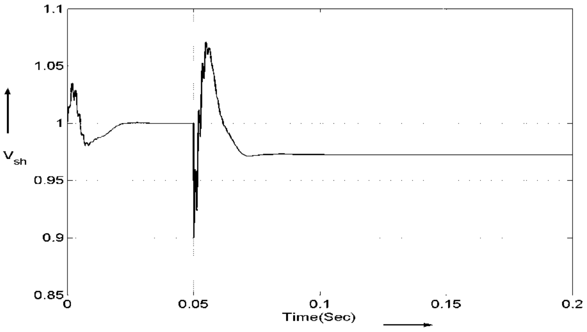

Fig 17(b): UPFC shunt voltage magnitude

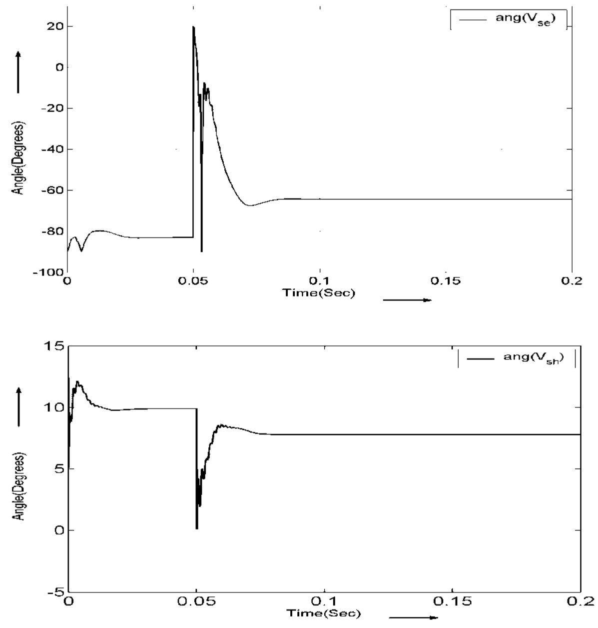

Fig. 17(c): Angles of series and shunt voltages of UPFC

The controller tracks the active and reactive power reference settings very quickly with limited overshoot. The controllers also regulate the ac-bus and dc-link voltage very quickly with the settling time of nearly one and half cycle (at 50 Hz). The result without the series transformer impedance and line charging is also simulated and is compared. It is found that effects of these are very significant on the performance of the system.

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APPENDIX

A. System data

The test system taken for simulation study of UPFC is shown in Fig 2, which is one-line circuit diagram model of UPFC installed in a system. A 220 kV, 100 MVA, 150 km long line is considered for simulation study. The system data taken for the simulation study are as follows:

$\omega_{Base}= 2\pi f_0$, f_0 =50Hz, R_s=0.01 pu, X_s =0.15 pu, R_r=0.0248 pu, X_r=0.1265 pu, pu, C_y=0.1008 pu, R_{sh} = 0.04 pu X_{sh} = 0.1, R_{se} = 0.01 pu, X_{se} = 0.025 pu, g_c= 0.0067 pu, b_c= 1.5708 pu.

B. PI Controller data

The parameters of the PI controllers are determined by a thorough and repeated study of the system response under various operating condition. The PI gains, which give the best responses under all the tested conditions, are listed below:

$$k_{sed}= 0.5,\ k_{ised}= 75,\ k_{seq}= 0.75,\ k_{iseq}=225;$$

$$k_{sh1}=0.5,\ k_{ish1}=1000,\ k_{sh2}=1.75,\ k_{ish2}=2000.$$

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