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Power Flow Improvement in Transmission Line using UPFC

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Abstract: UPFC is the most comprehensive multivariable flexible ac transmission system (FACTS) controller. Simultaneous control of multiple power system variables with UPFC posses enormous difficulties. This paper proposes a new real and reactive power coordination controller for a unified power flow controller (UPFC). The basic control for the UPFC is such that the series converter of the UPFC controls the transmission line real/reactive power flow and the shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the DC link capacitor voltage. In steady state, the real power demand of the series converter is supplied by the shunt converter of the UPFC. To avoid instability/loss of DC link capacitor voltage during transient conditions, a new real power coordination controller has been designed. The need for reactive power coordination controller for UPFC arises from the fact that excessive bus voltage (the bus to which the shunt converter is connected) excursions occur during reactive power transfers. A new reactive power coordination controller has been designed to limit excessive voltage excursions during reactive power transfers. The shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. The series converter of the UPFC provides simultaneous control of real and reactive power flow in the transmission line the shunt converter has been modeled as a 4-module converter. The series converter consists of two sets of converters. One set of converter is used for the real power flow control and the other set of converter is used for the reactive power flow control. Recent advances in high voltage IGCT technology allow for higher switching frequencies with lower losses. This allows for practical implementation of PWM control. The switching frequency for the converters has been chosen to be nine times the fundamental. Here we use mat lab/simulink for the simulation purpose and outputs are verified in the scope.

Keywords: Flexible AC Transmission System (FACTS), Unified Power Flow Controller (UPFC), PWM, IGCT.

I. INTRODUCTION

UPFC is the most comprehensive multivariable flexible ac transmission system (FACTS) controller. Simultaneous control of multiple power system variables with UPFC posses enormous difficulties. In addition, the complexity of the UPFC control increases due to the fact that the controlled and the control variables interact with each other. UPFC which consists of a series and a shunt converter connected by a common dc link capacitor can simultaneously perform the function of transmission line real/reactive power flow control in addition to UPFC bus voltage/shunt reactive power control. The shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. The series converter of the UPFC controls the transmission line real/reactive power flows by injecting a series voltage of adjustable magnitude and phase angle. The interaction between the series injected voltage and the transmission line current leads to real and reactive power exchange between the series converter and the power system. Under steady state conditions, the real power demand of the series converter is supplied by the shunt converter. But during transient conditions, the series converter real power demand is supplied by the dc link capacitor. If the information regarding the series converter real demand is not conveyed to the shunt converter control system, it could lead to collapse of the dc link capacitor voltage and subsequent removal of UPFC from operation. Very little or no attention has been given to the important aspect of coordination control between the series and the shunt converter control systems.

The real power coordination discussed is based on the known fact that the shunt converter should provide the real power demand of the series converter. In this case, the series converter provides the shunt converter control system an equivalent shunt converter real power reference that includes the error due to change in dc link capacitor voltage and the series converter real power demand. The control system designed for the shunt converter in causes excessive delay in relaying the series converter real power demand information to the shunt converter. This could lead to improper coordination of the overall UPFC control system and subsequent collapse of dc link capacitor voltage under transient conditions. In this paper, a new real power coordination controller has been developed to avoid instability/excessive loss of dc link capacitor voltage during transient conditions. In contrast to real power coordination between the series and shunt converter control system, the control of transmission line reactive power flow leads to excessive voltage excursions of the UPFC bus voltage during reactive power transfers. This is due to the fact that any change in transmission line reactive power flow achieved by adjusting the magnitude/phase angle of the series injected voltage of the UPFC is actually supplied by the shunt converter. The excessive voltage excursions of the UPFC bus voltage is due to absence of reactive power coordination between the series and the shunt converter control system. This aspect of UPFC control has also not been investigated. A new reactive power coordination controller between the series and the shunt converter control system has been designed to reduce UPFC bus voltage excursions during reactive power transfers. In this paper, a UPFC control system that includes the real and reactive power coordination controller has been designed and its performance evaluated.

II. UNIFIED POWER FLOW CONTROLLER (UPFC)

Gyugyi proposed the Unified Power Flow Controller (UPFC) concept in 1991. The UPFC was devised for the real time control and dynamic compensation of ac transmission systems, providing multifunctional flexibility required to solve many of the problems facing the delivery industry. Within the framework of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line (i.e., voltage, impedance and phase angle), and this unique capability is signed by the adjective “unified” in its name. Alternatively, it can independently control both the real and reactive power flows in the line.

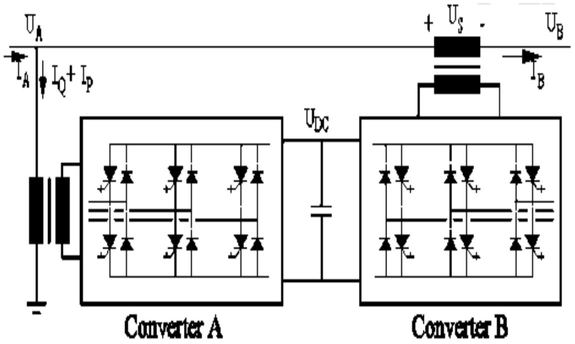


Fig.1. Basic circuit arrangement of unified power flow controller.

A. Circuit Arrangement

In the presently used practical implementation, The UPFC consists of two switching converters, which in the implementations considered are voltage source inverters using gate turn-off (GTO) thyristor valves, as illustrated in the Fig.1. These back to back converters labeled “Inverter 1 and “Inverter 2” in the figure, are operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ac to ac power converter in which the real power can freely flow in either direction between the ac terminals of the two inverters and each inverter can independently generate (or absorb) reactive power at its own ac output terminal.

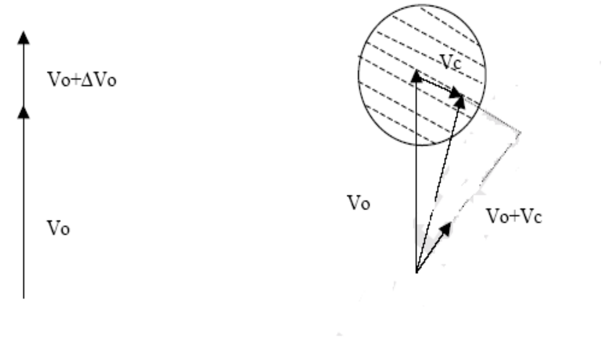
B. Operation of UPFC

Inverter 2 provides the main function of the UPFC by injecting an ac voltage V_{pq} with controllable magnitude V_{pq} ($0 \leq V_{pq} \leq V_{pqmax}$) and phase angle $\rho (0 \leq \rho \leq 360)$, at the power frequency, in series with the line via an insertion transformer. The injected voltage is considered essentially as a synchronous voltage source. The transmission 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 insertion transformer) is converted by the inverter into dc power that appears at the dc link as positive or negative real power demanded. The reactive power exchanged at the ac terminal is generated internally by the inverter. The basic function of inverter 1 is to supply or absorb the real power demanded by Inverter 2 at the common dc link. This dc link power is converted back to ac and coupled to the transmission line via a shunt-connected transformer. Inverter 1 can also generate or absorb controllable reactive power, if it is desired, and there by it can provide independent shunt reactive compensation for the line. It is important to note that where as there is a closed “direct” path for the real power negotiated by the action of series voltage injection through Inverters 1 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by inverter 2 and therefore it does not flow through the line. Thus, Inverter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independently of the reactive power exchanged by the Inverter 2. This means there is no continuous reactive power flow through UPFC.

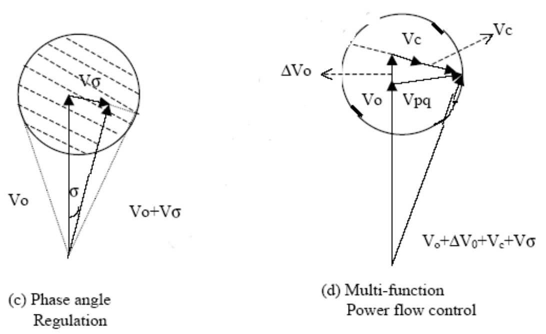
C. Basic Control Functions

Operation of the UPFC from the standpoint of conventional power transmission based on reactive shunt compensation, series compensation, and phase shifting, the UPFC can fulfill these functions and thereby meet multiple control objectives by adding the injected voltage V_{pq},with appropriate amplitude.

Terminal Voltage Regulation, similar to that obtainable with a transformer tap-changer having infinitely small steps, as shown at (a) where $V_{pq} = \Delta V$ (boldface letters represent phasors) is injected in-phase (or anti-phase) with V_o.



(a) voltage regulation (b) series compensation



(c) Phase angle Regulation

(d) Multi-function Power flow control

Fig.2.Basic UPFC Control Functions: a) Voltage Regulate, B) Series Compensation, C) Angle Regulation And D) Multifunction Power.

Series capacitor compensation is shown at (b) where $V_{pq}=V_c$ is in quadrature with the line current I.

Transmission angle Regulation (phase shifting) is shown at (c) where $V_{pq}=V_o$ is injected with angular relationship with respect to V_o that achieves the desired s phase shift (advance or retard) without any change in magnitude.

Multifunctional Power Flow Control, executed by simultaneous terminal voltage regulation, series capacitive compensation, and phase shifting, is shown at (d) where $V_{pq}=\Delta V+V_c+V_o$.

D. Basic Principles of P and Q Control

Consider Fig.2 At (a) a simple two machine (or two bus ac inter-tie) system with sending end voltage V_s, receiving-end voltage V_r, and line (or tie) impedence X (assumed, for simplicity, inductive) is shown. At (b) the voltages of the system in the form of a phasor diagram are shown with transmission angle δ and $|V_s|=|V_r|=V$. At (c) the transmitted power P ($P=V_2/X \sin\delta$) and the reactive power $Q=Q_s=Q_r$ ($Q=V_2/X\ (1-\cos\delta)$) supplied at the ends of the line are shown plotted against angleδ. At (d) the reactive power $Q=Q_s=Q_r$ is shown plotted against the transmitted power corresponding to “stable values of δ” (i.e., $0<=\delta<=90^o$). Basic power system of fig with the well known transmission characteristics is introduced for the purpose of providing a vehicle to establish the capability of the UPFC to control the transmitted real power P and the reactive power demands, Q_s and Q_r, at the sending end, respectively, the receiving end of the line. Consider Fig.2. The simple power system of Fig is expanded to include the UPFC. The UPFC is represented by a controllable voltage source in series with the line which, as explained in the previous section, can generate or absorb reactive power that it, or absorbed from it, bye the sending end generator.

The UPFC in series with the line is represented by the phasor V_{pq} having magnitude $V_{pq}(0 \le V_{pq} \le V_{pqmax})$ and angle ρ ($0 \le \rho \le 360$) measured from the given phase position of phasor Vs, as illustrated in the figure. The line current represented by the phasor I, flows through the series voltage source, V_{pq} and generally results in both reactive and real power exchange. In order to represent UPFC properly, the series voltage source is stipulated to generate only the reactive power Q_{pq} it exchanges with the line. Thus the real power P_{pq} it negotiates with the line is assumed to be transferred to the sending-end generator excited. This is in arrangement with the UPFC circuit structure in which the dc link between the two constituent inverters establish a bi-directional coupling for real power flow between the injected series voltage source and the sending end bus. As Fig.3 implies, in the present discussion it is further assumed for clarity that the shunt reactive compensation capability of the UPFC not utilized. This is the UPFC shunt inverter is assumed to be operated at unity power factor, its sole function being to transfer the real power demand of the series inverter to the sending-end generator. With these assumptions, the series voltage source, together with the real power coupling to the sending end generator as shown in fig.4, is a an accurate representation of the basic UPFC.

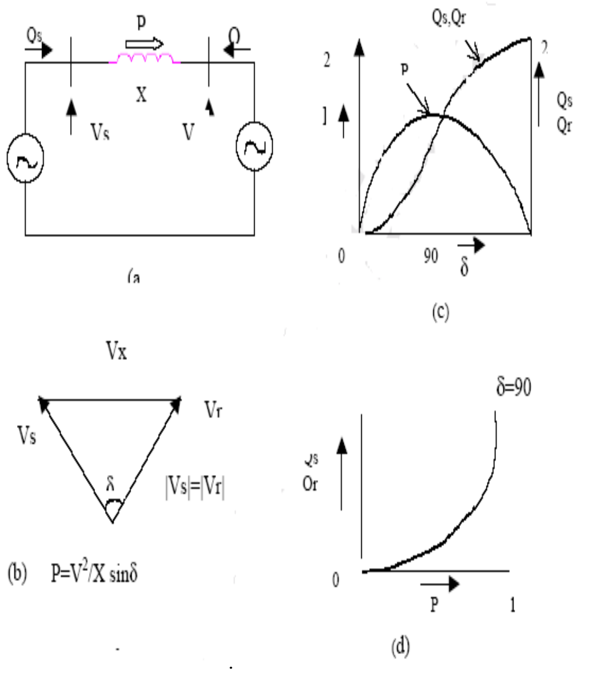


Fig.3. Simple two machine system (a) Related voltage phasor (b) Real and Reactive power verses transmission angle (c) sending end /receiving end reactive power v/s transmitted real power.

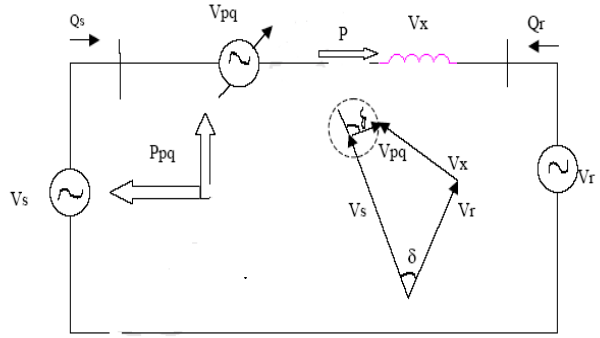


Fig.4. Two machine system with the unified power flow controller.

It can be observed in Fig that the transmission line "sees" V_s+V_{pq} as the effective sending end voltage. Thus it is clear that the UPFC effects the voltage (both its magnitude and angle) across the transmission line and therefore it is reasonable to expect that it is able to control, by varying the magnitude and angle of V_{pq}, the transmittable real power as well as the reactive power demand of the line at any given transmission angle between the sending-end and receiving-end voltages.

III. MODELLING OF CASE STUDY

A. Control Strategy for UPFC

Shunt Converter Control Strategy: The shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. In this case, the shunt converter voltage is decomposed into two components. One component is in-phase and the other in quadrature with the UPFC bus voltage. De-coupled control system has been employed to achieve simultaneous control of the UPFC bus voltage and the dc link capacitor voltage.

Series Converter Control Strategy: The series converter of the UPFC provides simultaneous control of real and reactive power flow in the transmission line. To do so, the series converter injected voltage is decomposed into two components. One component of the series injected voltage is in quadrature and the other in-phase with the UPFC bus voltage. The quadrature injected component controls the transmission line real power flow. This strategy is similar to that of a phase shifter. The in-phase component controls the transmission line reactive power flow. This strategy is similar to that of a tap changer.

B. Basic Control System

Shunt Converter Control System: Fig.5 shows the de-coupled control system for the shunt converter. The D-axis control system controls the dc link capacitor voltage and the Q-axis control system controls the UPFC bus voltage /shunt reactive power. The details of the de-coupled control system design can be found .The de-coupled control system has been designed based on linear control system techniques and it consists of an outer loop control system that sets the reference for the inner control system loop. The inner control system loop tracks the reference.

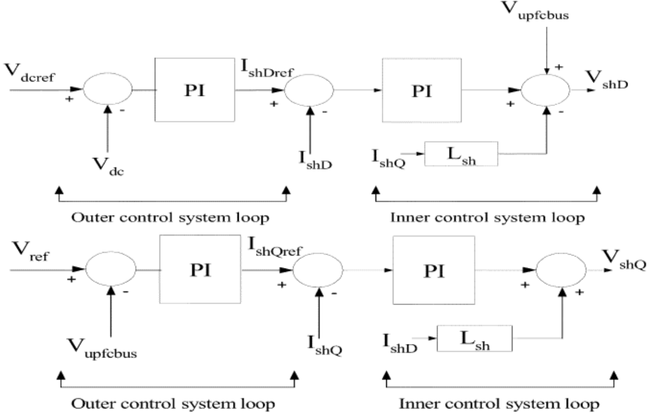


Fig.5. De-coupled D-Q axis shunt converter control system.

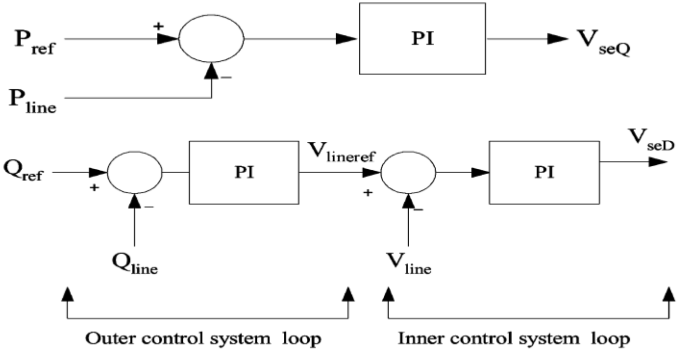


Fig.6. Series converter real and reactive power flow control system.

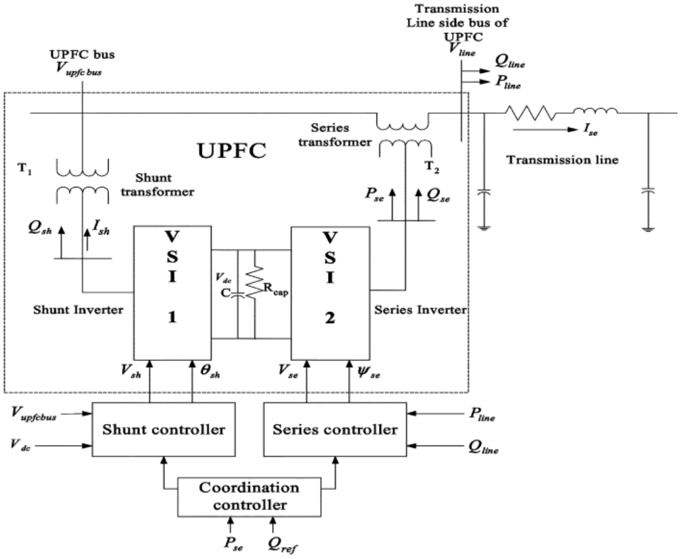


Fig.7. UPFC connected to a transmission line.

Series Converter Control System: Fig.6 shows the overall series converter control system. The transmission line real power flow is controlled by injecting a component of the series voltage in quadrature with the UPFC bus voltage. The transmission line reactive power is controlled by modulating the transmission line side bus voltage reference. The transmission line side bus voltage is controlled by injecting a component of the series voltage in-phase with the UPFC bus voltage.

C. Real And Reactive Power Coordination Controller

Real Power Coordination Controller: To understand the design of a real power coordination controller for a UPFC, consider a UPFC connected to a transmission line as shown in Fig.7. The interaction between the series injected voltage and the transmission line current leads to exchange of real power between the series converter and the transmission line. The real power demand of the series converter causes the dc link capacitor voltage to either increase or decrease depending on the direction of the real power flow from the series converter. This decrease/increase in dc link capacitor voltage is sensed by the shunt converter controller that controls the dc link capacitor voltage and acts to increase/decrease the shunt converter real power flow to bring the dc link capacitor voltage back to its scheduled value. Alternatively, the real power demand of the series converter is recognized by the shunt converter controller only by the decrease/increase of the dc link capacitor voltage. Thus, the shunt and the series converter operation are in a way separated from each other. To provide for proper coordination between the shunt and the series converter control system, a feedback from the series converter is provided to the shunt converter control system.

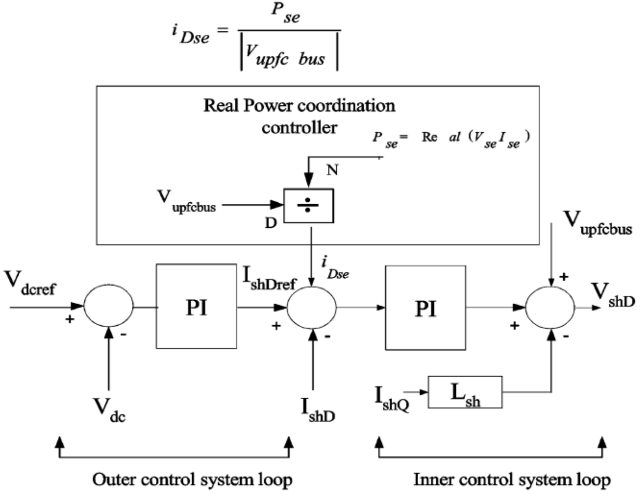


Fig.8. D-axis shunt converter control system with real power coordination controller.

The feedback signal used is the real power demand of the series converter. The real power demand of the series converter is converted into an equivalent D-axis current for the shunt converter. By doing so, the shunt converter responds immediately to a change in its D-axis current and supplies the necessary series converter real power demand. The equivalent D-axis current is an additional input to the D-axis shunt converter control system as shown in Fig.8.

$$i_{Dse} = \frac{P_{se}}{|V_{upfc\ bus}|}. \qquad (1)$$

Equation shows the relationship between the series converter real power demand P_{se} and the shunt converter D-axis current iD_{se}.

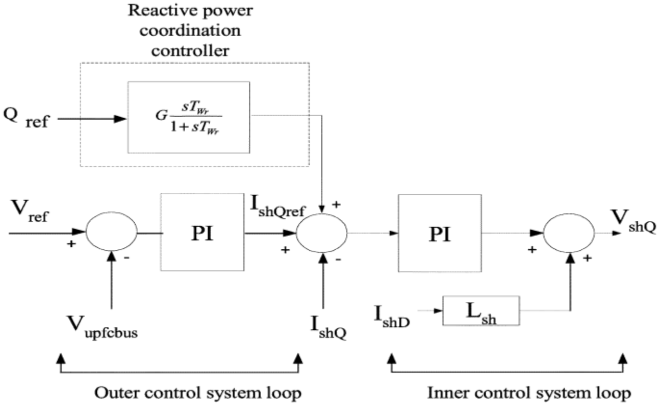


Fig.9. Shunt converter Q-axis controller with reactive power coordination controller.

The real power demand of the series converter P_{se} is the real part of product of the series converter injected voltage V_{se} and the transmission line current I_{se}. $V_{upfcbus}$, iD_{se} represent the voltage of the bus to which the shunt converter is connected and the equivalent additional D-axis current that should flow through the shunt converter to supply the real power demand of the series converter. As shown in Fig.8, the equivalent D-axis additional current signal (iD_{se}) is fed to the inner control system, thereby increasing the effectiveness of the coordination controller. Further, the inner control system loops are fast acting PI controllers and ensure fast supply of the series converter real power demand P_{se} by the shunt converter.

Reactive Power Coordination Controller: The in-phase component (V_{seD}) of the series injected voltage which has the same phase as that of the UPFC bus voltage, has considerable effect on the transmission line reactive power (Q_{line}) and the shunt converter reactive power (Q_{sh}). Any increase/decrease in the transmission line reactive power (Q_{line}) due to in-phase component (V_{seD}) of the series injected voltage causes an equal increase/decrease in the shunt converter reactive power (Q_{sh}). In short, increase/decrease in transmission line reactive power is supplied by the shunt converter. Increase/decrease in the transmission line reactive power also has considerable effect on the UPFC bus voltage. The mechanism by which the request for transmission line reactive power flow is supplied by the shunt converter is as follows. Increase in transmission line reactive power reference causes a decrease in UPFC bus voltage. Decrease in UPFC bus voltage is sensed by the shunt converter UPFC bus voltage controller which causes the shunt converter to increase its reactive power output to boost the voltage to its reference value. The increase in shunt converter reactive power output is exactly equal to the increase requested by the transmission line reactive power flow controller (neglecting the series transformer T2 reactive power loss).

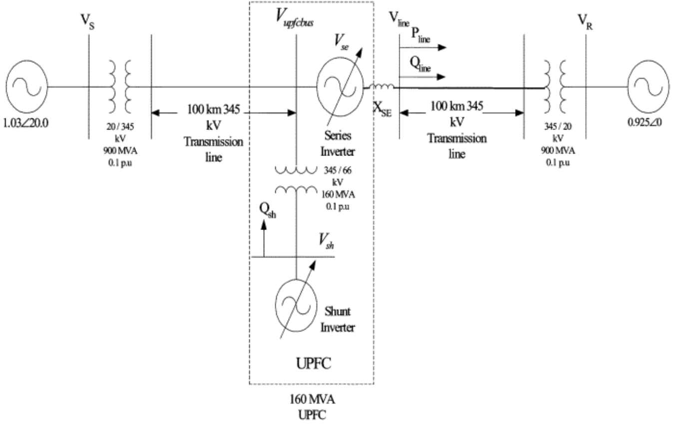


Fig.10. Power system with UPFC.

Similarly, for a decrease in transmission line reactive power, the UPFC bus voltage increases momentarily. The increase in UPFC bus voltage causes the shunt converter to consume reactive power and bring the UPFC bus voltage back to its reference value. The decrease in the shunt converter reactive power is exactly equal to the decrease in transmission line reactive power flow (neglecting the reactive power absorbed by the series transformer T2). In this process, the

UPFC bus voltage experiences excessive voltage excursions. To reduce the UPFC bus voltage excursions, a reactive power flow coordination controller has been designed. The input to the reactive power coordination controller is the transmission line reactive power reference. Fig.9 shows the shunt converter Q-axis control system with the reactive power coordination controller. The washout circuit represents the reactive power coordination controller. The gain of the washout circuit has been chosen to be 1.0. This is because, any increase/decrease in the transmission line reactive power flow due to change in its reference is supplied by the shunt converter as shown in Fig.10. The washout time constant is designed based on the response of the power system to step changes in transmission line reactive power flow without the reactive power coordination controller.

IV. SIMULATION MODEL AND RESULTS

Simulation model and results of this paper is as shown in Figs.11 to 15.

A. Model Of Real And Reactive Power Coordination

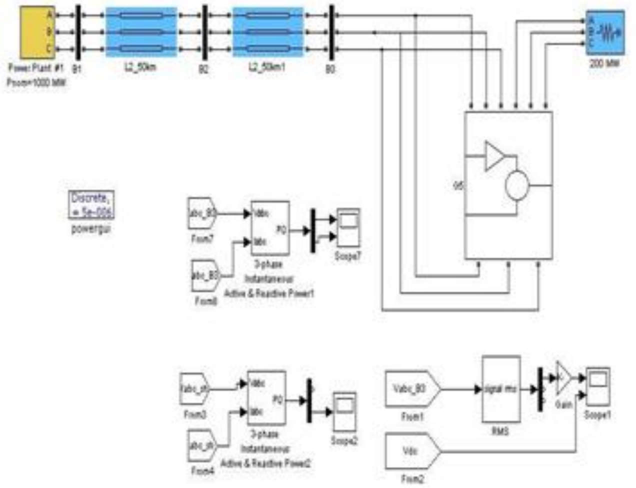


Fig.11.Model of Real and Reactive Power Coordination.

B. Simulation For Real and Reactive Power Without Coordination

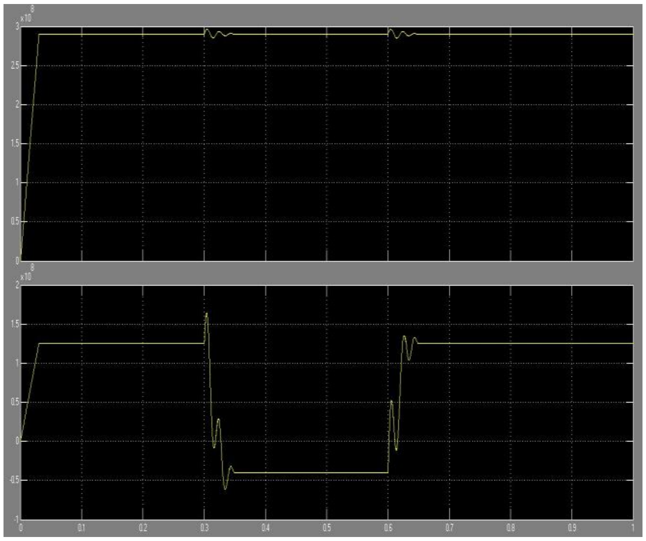


Fig.12.

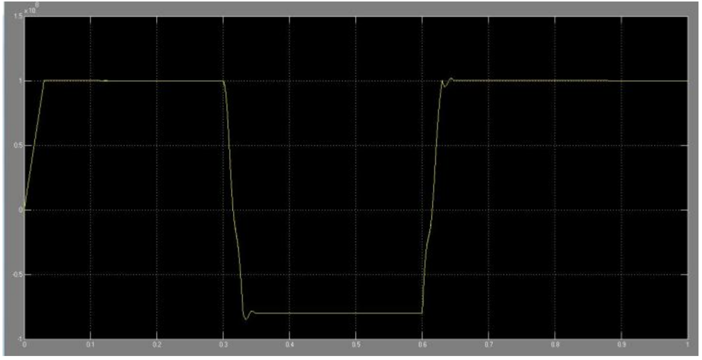


Fig.13.

C. Simulation For Real And Reactive Power With Coordination

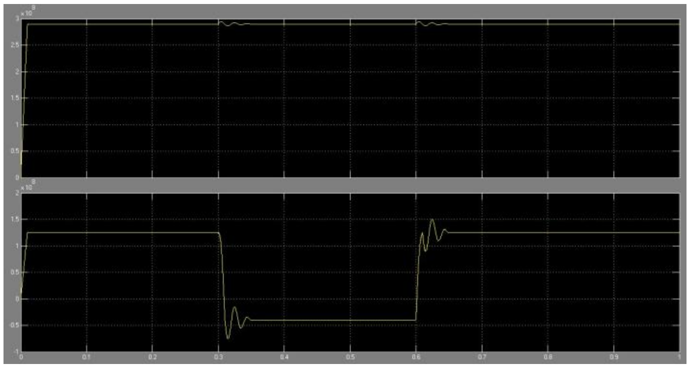


Fig.14.

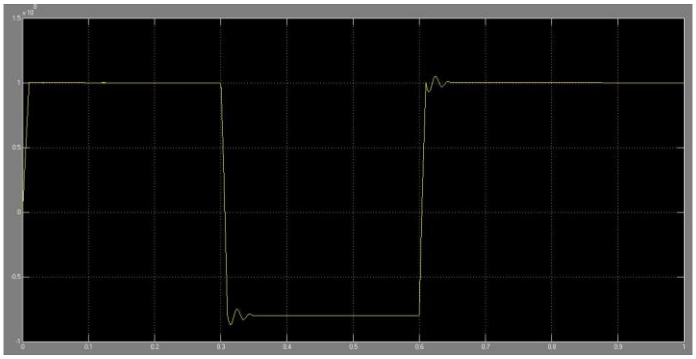


Fig.15.

V. CONCLUSION

This paper has presented a new real and reactive power coordination controller for a UPFC. The basic control strategy is such that the shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. The series converter controls the transmission line real and reactive power flow. The contributions of this work can be summarized as follows.

- Two important coordination problems have been addressed in this paper related to UPFC control. One, the problem of real power coordination between the series and the shunt converter control system. Second, the problem of excessive UPFC bus voltage excursions during reactive power transfers requiring reactive power coordination.
- Inclusion of the real power coordination controller in the UPFC control system avoids excessive dc link capacitor

voltage excursions and improves its recovery during transient conditions. MATLAB simulations have been conducted to verify the improvement in dc link voltage excursions during transient conditions. Significantly reducing UPFC bus voltage excursions during reactive power transfers. The effect on transmission line reactive power flow is minimal. MATLAB simulations have shown the improvement in power oscillation damping with UPFC.

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