A Performance Analysis of Simultaneously Controlled UPFC at varied Metrics

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Abstract: *The paper discusses coordinated excitation and UPFC control to improve power system transient stability and voltage stability. In the design of an excitation controller, the power system is linearized using a direct feedback technique. A robust approach is used to deal with the uncertainties caused by parameter variations and the inclusion of UPFC controller. Only local measurements are required for designing the excitation controller. The series branch of the UPFC is designed to damp the power oscillation during transients, while the shunt branch aims at maintaining the bus voltage. The performance of the proposed controller is tested on a single-machine, single-load power system. Simulation results show that the coordinated excitation and UPFC control is effective for transient stability enhancement. Both of the series and shunt branch control of UPFC help improve transient stability. The impact of the controller on voltage stability is studied through control of series and shunt controllers. It is shown that the feasibility region can be greatly increased.*

Keywords: FACTS, UPFC, Transient stability

I. INTRODUCTION.

POWER system stability is very important, especially for a large-scale system. In 2003, a record number of total blackouts happened in North America as well as in large portion of Europe, which affected 50 million people and caused huge economy losses. In order to avoid those unwanted events, power system stability enhancement becomes paramount important.

The promising concept of the Flexible AC Transmission System (FACTS) makes it possible to achieve fast and reliable power system control by means of power electronic devices. FACTS can alter the impedance of a line and influence the routing of power within a system and between systems. It will be necessary to have a coordinated operation of FACTS devices. The Unified Power Flow Controller (UPFC), which is the most versatile FACTS device, has the capabilities of controlling power flow in the transmission line, improving the transient stability, mitigating system oscillations and providing voltage support [1][2][5]. It can control all three basic power transfer parameters like line impedance, voltage magnitude and phase angle. Independently or simultaneously in any appropriate combinations. Efforts in erstwhile research have focused mainly on controlling system steady state power flows and improving system stability.

II. RELATED WORK.

This paper will present the dynamic control of the UPFC. Firstly, a dynamic model of the UPFC is derived based on the synchronous `d-q-frame` in this work. Secondly, the proposed integral based control strategy for the shunt part and the series part of UPFC are described respectively in the same synchronous frame and used to provide real and reactive power flow control along the transmission line at its series output end, while regulating the magnitude of the voltage at its shunt input end and maintaining the `DC-Link` capacitor voltage constant.

Finally digital simulation results obtained from two power systems are presented to illustrate the contributions of the new control approach. Fig. 1 Connection of a UPFC to a simplified two-bus system

III. MODELLING OF S-UPFC.

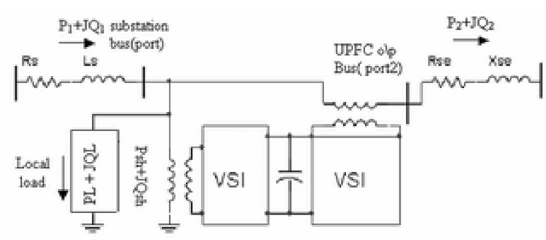


Fig. 1 UPFC Model

Fig. 1 shows the system configuration of a UPFC, installed between two machines through a transmission line. The UPFC consists of a combination of a shunt and series branches, which take the form of two transformers and two voltage source inverters sharing a common DC link with a DC storage capacitor [1]. The series connected inverter injects a voltage with controllable magnitude and phase angle in series with the transmission line, therefore providing real and reactive power to the transmission line. The shunt-connected inverter provides the real power drawn by the series branch. The first part of the investigation is to establish a suitable UPFC dynamic model. This paper proposes a UPFC current injection model, which is obtained from some modification of UPFC power injection model in [3]. The proposed model can easily be incorporated in the Power System Toolbox, which is a powerful dynamic simulation program.

After establishing the UPFC current injection model, a proper control method is necessary for the model to improve the dynamic stability of the power system. In [5] the improvement of transient stability using UPFC was investigated and a UPFC model and its control method were proposed. But the control method requires detailed information of the whole power system. It is difficult to realize the control method. In [1] the mechanism of the three control methods of UPFC, namely in-phase voltage control, quadrature voltage control and shunt compensation, in improving the transient stability of power systems was investigated. But the authors considered these three methods separately and did not give much information about dynamic performance. In [2] it proposed decoupled control algorithms of the two components of UPFC series voltage, which are quadrature and in phase with the line current, by active and reactive power respectively. The paper presents very helpful information about how to use UPFC to improve power system dynamic stability. However, the decoupled control algorithms are based on approximate relationship. The exact relationship inherently implies the coordinated control of active and reactive power.

The paper also gives the time domain simulation of UPFC by varying different parameters of the power system. But in this system it seems that we have better choices of input signals rather than active and reactive power.

IV. CONTROLLER DESIGN

Series Injected Voltage Controller

In this section we consider the control of real power using series voltage injection. We carry out analysis on the simplified system shown below in Fig 2. The differential equations for the current at port 2 in the D-Q (synchronously rotating at system frequency ω_0) frame of reference are given by:

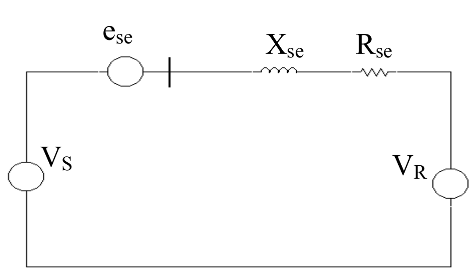


Fig 2: Simplified system with UPFC

Where, $V_{2d}=V_{1d}+e_{Dse}$
$V_{2q}=V_{1q}+e_{Qse}$

The subscripts 'D' and 'Q' denote the variables in D-Q reference frame V_{2D}, V_{2Q}= D-Q components of voltages at UPFC port 2 Power at the receiving end bus P_R is approximately equal to that of port 2 (P_2) of the UPFC in the study state; therefore we control the power at port 2 since the feed back signal is readily available.

Power delivered by the series converter is

$$P_2 = V_{2D} i_{Dse} + V_{2Q} i_{Qse} \tag{1}$$

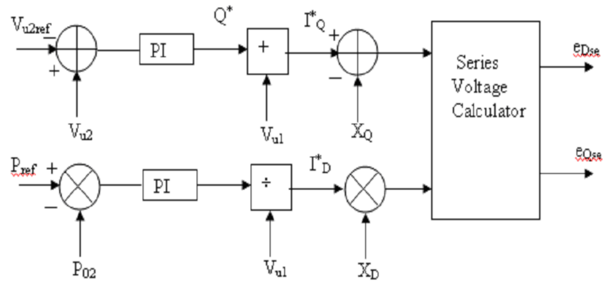
From the above equations (1) we will get the actual D-Q currents flowing in the line. The required real power flow and the port 2 voltage set a reference for D-Q currents.

Port 2 Voltage Control

The voltage at port 2 of the UPFC is algebraically related to that at port 1 and the series voltage injected for power flow control. (For simplicity the series transformer reactance is clubbed with the line impedance). Since all the quantities are locally available, we can easily calculate the series voltage to be injected to obtain desired magnitude of V_2.

The series injected controller diagram in d-q axis referred to bus 1 is given by:

$$\begin{aligned} V_2 &= \sqrt{(V_{2D})^2 + (V_{2Q})^2} \\ &= \sqrt{(V_{1D}+e_{Dse})^2 + (V_{1Q}+e_{Qse})^2} \end{aligned} \tag{2}$$

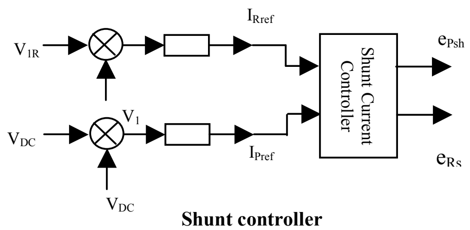


Series Injected Voltage Controller

By varying the magnitude and angle of the shunt converter voltage controls the shunt current. The dynamic equations in the D-Q frame are given by,

$$\begin{aligned} \frac{di_{Dsh}}{dt} &= -\frac{r_{sh}\omega}{x_{sh}} i_{Dsh} + \omega\, i_{Qsh} + \frac{\omega_b}{x_{sh}}(e_{Dsh} - v_{1D}) \\ \frac{di_{Qsh}}{dt} &= -\frac{r_{sh}\omega}{x_{sh}} i_{Qsh} - \omega\, i_{Dsh} + \frac{\omega_b}{x_{sh}}(e_{Qsh} - v_{1Q}) \end{aligned} \tag{3}$$

Where, r_{sh}, X_{sh} =shunt transformer resistance and leakage reactance respectively e_{Dsh}, e_{Qsh}=converter output voltage components V_{1D}, V_{1Q}=voltage components at the bus into which current injected (port 1 of UPFC).



Shunt controller

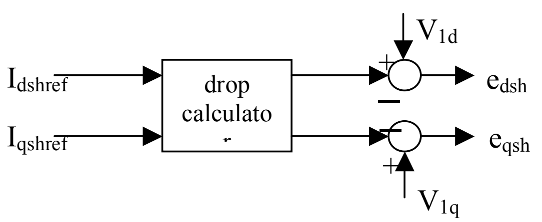
In shunt current control block we are calculating the shunt converter output voltages through the drop calculator block by using I_{dref} and I_{qref}.

The differential equations used in drop calculator are:

$$e_{Rsh} = -R_{sh}\, i_{dshref} - \frac{x_{sh}}{\omega_b}\frac{d\, i_{dshref}}{dt} + X_{sh}\, i_{qshref} + V_{1d}$$

$$e_{psh} = -R_{sh}\, i_{qshref} - \frac{x_{sh}}{\omega_b}\frac{d\, i_{qshref}}{dt} - X_{sh}\, i_{dshref} + V_{1q}$$

(4)



Port 1 voltages are calculated by adding shunt and series currents and from the given sending end voltage. The differential equations for port 1 voltage calculation is:

$$V_{1D} = -R_{se} i_{dl} - \frac{x_{se}}{\omega_b}\frac{di_{dl}}{dt} + X_{se} i_{ql} + V_{sD}$$

$$V_{1Q} = -R_{se} i_{ql} - \frac{x_{se}}{\omega_b}\frac{di_{ql}}{dt} - X_{se} i_{dl} + V_{sQ}$$

(5)

The dynamical equation for the capacitor is given by

$$\frac{dv_{Dc}}{dt} = -\frac{g_{cap}\omega_b}{b_{cap}} V_{Dc} + \frac{\omega_b}{b_{cap}}(i_{dsh} - i_{qsh})$$

(6)

Any real power drawn / supplied by the series branch or by shunt branch (due to real current injection i_{psh}) manifests as DC side currents I_{Dc}^{ser} and I_{dc}^{sh} respectively. Since we allow variable series voltage injection, and due to losses, the capacitor voltage tends change.

V. UPFC MODEL AND ITS CONTROL.

The UPFC was derived by assuming that the series and parallel converters are treated as ideal controllable voltage sources that the values of the fundamental components of the line currents are locally available. The UPFC is modeled by combining the shunt and series branches coupled by the dc voltage control branch. Local load is added at port 1 of the UPFC and is shown in the figure 1. Shunt converter was modeled to inject currents into the port1. Inputs for the shunt converter block are V_{u1ref}, V_{dcref}. In these two PI control blocks are used. The PI parameters are tuned accordingly to get required output. The transmission line1 model was used to calculate the port1 voltage and the real and reactive power flows (P1 and Q1) from the sending end at port1. Inputs to this block are sending end voltages (d-q quantities). Transmission line2 was modeled to calculate the series current flowing in the line from port2 to the receiving end bus. Inverter dc side control model was used to find the shunt converter output voltages and its RMS value. Power calculator block is used to calculate real and reactive shunt powers. To achieve real power and port2 controls we need to inject series voltage of appropriate magnitude and angle.

VSI Inverter Modelling

The PWM voltage source inverter was assumed to be instantaneous and infinitely fast to track the voltage reference template set by the control strategy, so it was implemented as a voltage amplifier with unity gain. Inputs to this block are P_{ref} and v_{u2ref}. In these two PI controllers was used to get the real and reactive power references at the port1. PI parameters used in real power reference loop are k_p=1, k_i=500, k_d=0.001. Derivative control used to limit the initial peak overshoot. PI parameters used in voltage control loop are k_p=20, k_i=7500.

Parameters of saturation blocks are set to [+0.5,-0.5] otherwise the output of the inverter goes to high values.

For a detailed picture of the UPFC model by combining various blocks is shown in *Appendix I.*

VI. PERFORMANCE ANALYSIS.

By analysing the above results for a step change in load at t=0.08sec, sudden change in q component of the voltage observed. At that time shunt converter RMS voltage rises to inject reactive power into the bus reactive power into the bus. Reactive power shown as negative i.e. shunt converter delivering lagging reactive power to the bus to keep the bus voltage constant.

When the load is switched on at T=0.08 sec reactive power flow in the line (Q2) increases. So the series converter voltage changes accordingly to supply the reactive power. In the above plots the real power consumed by the shunt converter is not equal to the real power delivered by the series converter. The reason is we are measuring the shunt converter real power at port1. So, we have to subtract the real power dissipated in the resistance in the shunt converter path from the shunt real power.

The rise and fall times observed when sudden load change occurred at T=0.08sec and at T=0.25sec in port1 voltage are given by T_r=0.025sec, T_f=0.02sec. The load powers given in the figure is that of the commanded powers and are different from the actual power drawn from the bus by the time constant of 1ms. This accounts for the higher rise time observed. The parameters of the controllers at different locations are tuned to get satisfactory gain when sudden changes in load.

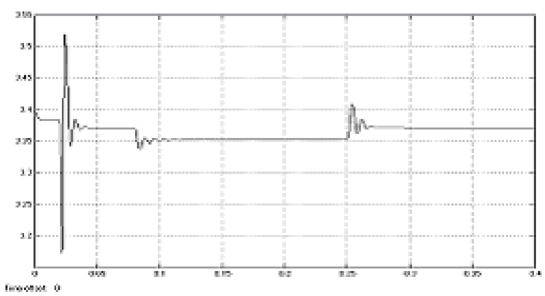
Initially there is no power flows from sending end to the receiving end because load angle is zero. When load changes the port1 voltage angle changes with respect to the receiving end, so there is a real power flow from port1 to the receiving end and from sending end to the port1. The rise and fall times observed in real power flow when load suddenly switched on are Tr=0.004sec and Tf=0.0001sec. The rise and fall times observed when load suddenly switched off at T=0.25sec are Tr=0.0001sec, Tf=0.0075sec.

VII. TIME SIMULATION RESULTS.

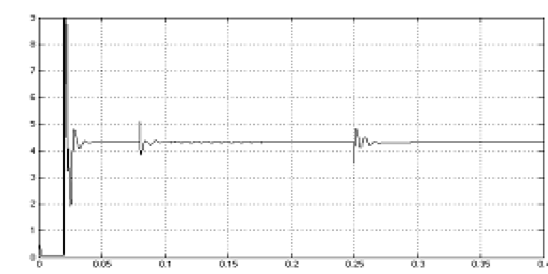
Steady Case – A Case Study

Vs=1 at an angle zero, load is 3 p.u with lagging power factor 0.8 Initially shunt controller is OFF. Shunt controller is ON at T= 0.04sec,P_{ref} =0,load switch ON at T=0.08sec and at T=0.25 sec load is thrown OFF and subsequently shunt control OFF. The simulation results are shown in the following graphs.

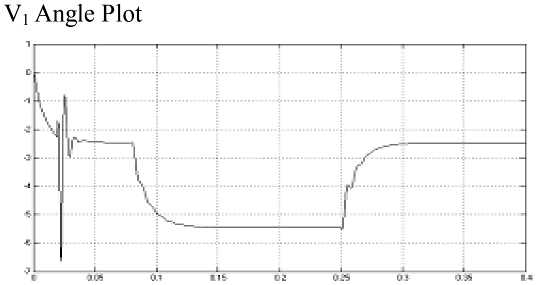
V_{1rmsa}Plot:



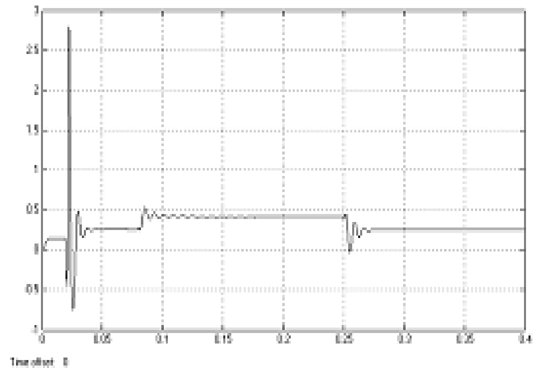
V_2 Angle Plot



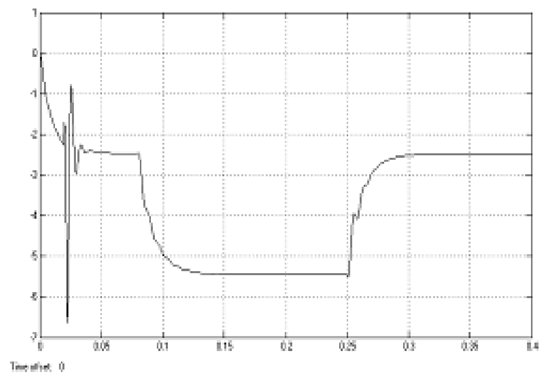
V_1 Angle Plot



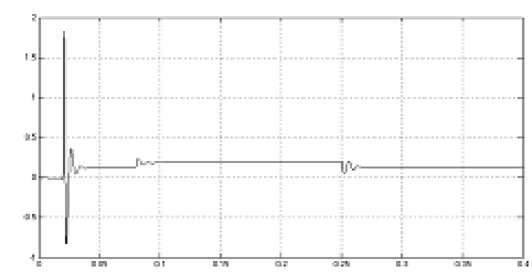
P_{sh} Plot



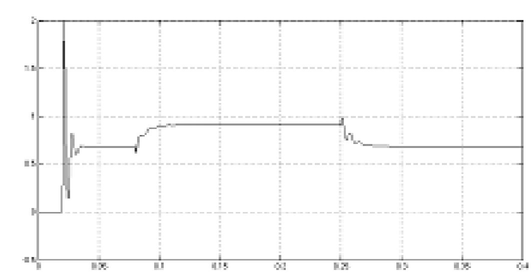
Q_{sh} Plot



P_{inv} Plot



Q_{inv} Plot



VIII .CONCLUSION

After observing simulation results we can conclude the transient stability is improved drastically in the systems where UPFC was installed. And also loading capability of transmission lines increases.

IX. REFERENCES

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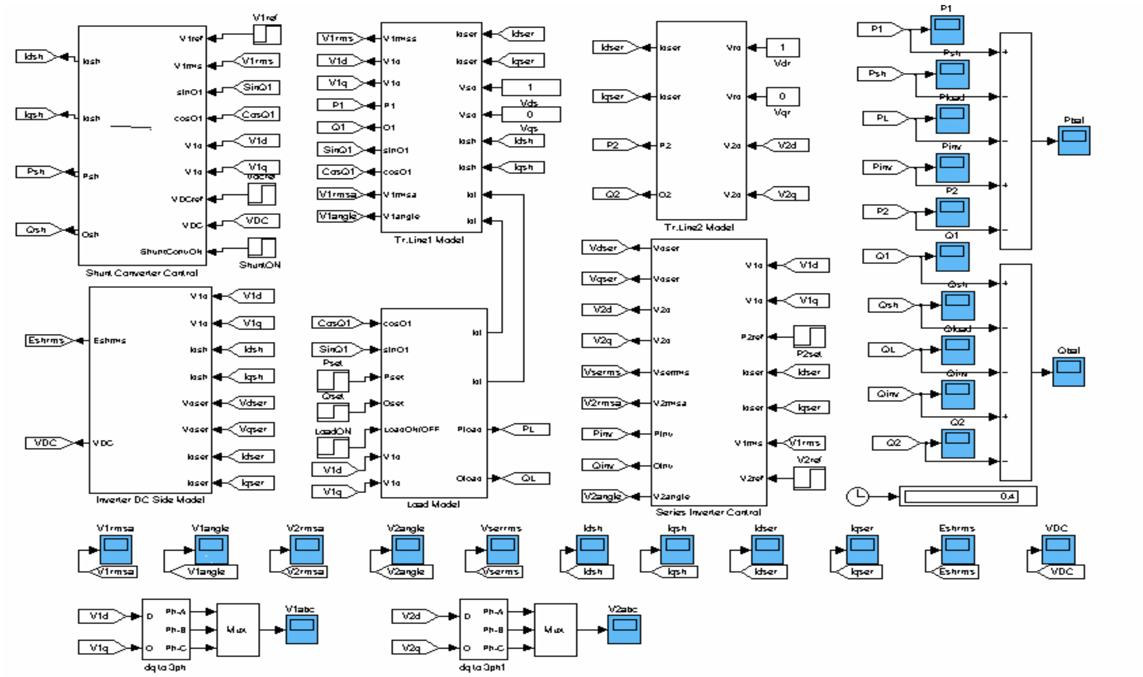
Appendix I.



Combined UPFC Model with all the blocks