AN INVESTIGATION OF INTEGRATED POWER FLOW CONTROLLER WITH POWER CONTROL METHODS ENHANCED BY SERIES COMPENSATION CONTROL

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ABSTRACT—The Unified Power Flow Controller (UPFC) is a multipurpose Flexible AC Transmission System which will improve the performance of a transmission line. The most preferred method of control of the series converter is power control. Alternate methods as series compensation method, phase shifter method, transformer like the control also finds their role in the control of the UPFC converters. This paper demonstrates the effectiveness of UPFC by employing a combination of control techniques integrated with series compensation control in improving the performance of the transmission line. It is shown that instead of keeping any one control method alone for controlling the performance of the line, if two methods are simultaneously implemented, there is marked improvement in the performance of the transmission system.

Keywords—P-Q control; series compensation; powerflow; direct voltage; quadrature current; control strategy

I. INTRODUCTION

As the world moves faster, the growth rate of the economy is solely represented by the consumption of electrical energy. The developments in the power scenario warrants not only the requirement of clean energy, the efficient transmission is needed taking into consideration of the limited resources. The explosive advancement in the energy scenario is marked by the introduction of the Flexible AC Transmission system the concept originated in 1991 [1] which was fueled from the innovations in the semiconductor devices [2]. The maximum versatile of these gadgets allows enhancing the damping of strength machine oscillations[3]. Basically consisting of a shunt and collection inverter, the UPFC can function in various modes for reaching shunt repayment, collection repayment or segment attitude reimbursement [4]. The easiness with which the mode can be changed is considered to be the most advantageous feature of UPFC [5-6].

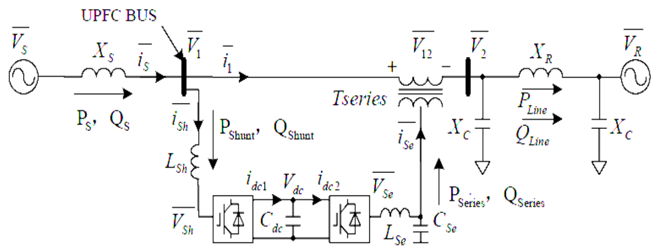


Fig. 1. Schematic of UPFC

transmission line current causes the series inverter to exchange real and reactive power with the transmission line. The real power exchange by the series inverter with the transmission line is supplied /absorbed by the DC link capacitor.

Three types of methods for real and reactive power flow control are explained below.

A. The UPFC Control Strategies

The foremost component of the UPFC is the series converter which fulfils the series compensation. This approach depends on generating the series voltage in quadrature with the transmission line modern permitting it to function equivalent to that of a variable collection capacitive reactance. This consequences inside the section angle of the series injected voltage to be in phase quadrature with the transmission line cutting-edge. By various the significance of this collection injected voltage that is in quadrature with the transmission line modern-day, the actual power waft may be controlled [7]. Combining the in-phase element and the quadrature issue, the significance and segment angle of the series injected voltage are acquired[8]. Initially the control of the UPFC converters has been based on the reference voltage control [9]. Even though it is the simplest control strategy, better control is obtained with voltage control Most of the published literature on the operation of UPFC has adopted this strategy [10-

11]. In fact, some published literature speaks about the use of phase angle along with cross couple control implemented in a laboratory prototype of UPFC [12]. A control strategy with shunt converter controlling the reactive power and series converter controlling the real power is found to yield better performance and is confirmed with experimental results on the prototype [13].

B. *Proposed Control Strategy*

The above-mentioned control methods are individually implemented and found to be giving reasonably good results. A fresh control method which combines the major advantage of the series compensation is incorporated along with the P-Q control is proposed. The series converter of UPFC has replaced the conventional series capacitor whose sole responsibility was to fulfill series compensation.

III. MODELING OF UPFC

As soon as the UPFC is associated to a transmission system, it enhances the performance of the line by improving the power flow through it, along with damping the oscillations arising from any disturbance in the system. The UPFC achieves this by injecting a series voltage into the system, at the point of connection. Hence we can justify the UPFC operation by a series voltage source VC as shown in the equivalent circuit below.

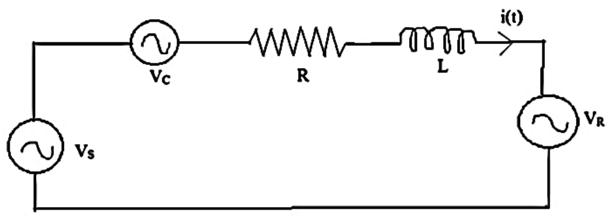


Fig. 2. Equivalent Circuit of UPFC

Applying KVL, we can write the following equation to represent the operation of UPFC connected in a transmission system.

$$Ri(t) + L\frac{di}{dt} = V_S + V_C - V_R \quad (1)$$

Where R and L correspond to the transmission line parameters, i(t) is the current, V_S and V_R are the voltages at directing end and delivery end correspondingly and V_C is the compensating voltage.

$$Ri(t) + L\frac{d}{dt}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} v_{sa} + v_{Ca} - v_{Ra} \\ v_{sb} + v_{Cb} - v_{Rb} \\ v_{sc} + v_{Cc} - v_{Rc} \end{bmatrix} \quad (2)$$

With d-q transformation,

$$L\frac{di}{dt} + (R + j\,\omega_0 L)i = v_{sd} + v_{cd} - v_{Rd} + j(v_{sq} + v_{cq} - v_{Rq}) \quad (3)$$

This we can separate to get

$$L\frac{d\,i_d}{dt} + (R\,i_d - \omega_0 L\,i_q) = v_{sd} + v_{cd} - v_{Rd} \quad (4)$$

$$L\frac{d\,i_q}{dt} + (R\,i_q - \omega_0 L\,i_d = v_{sq} + v_{cq} - v_{Rq} \quad (5)$$

where ω_0 is the angular frequency.

$$\begin{bmatrix} R + L\,{}^{d}\!/_{dt} & -\omega_0 L \\ -\omega_0 L & R + L\,{}^{d}\!/_{dt} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_{sd} + v_{cd} - v_{Rd} \\ v_{sq} + v_{cq} - v_{Rd} \end{bmatrix} \quad (6)$$

But the active power is

$$P_{CONV} = v_{cd}\,i_d + v_{cq}\,i_q \quad (7)$$

Thus we get the power equation,

$$P_C = L\left(i_d\frac{di_d}{dt} + i_q\frac{di_q}{dt}\right) + R\left(i_d^2 + i_q^2\right) - \left[\left(v_{sd} - v_{Rd}\right)i_d + \left[\left(v_{sq} - v_{Rq}\right)i_q\right] \quad (8)$$

The various components of power in this equation can be interpreted as follows.

$R\left(i_d^2 + i_q^2\right)$ represents the power dissipation in the resistance.

The active power transmitted to the receiving end is given by the term $\left[\left(v_{sd} - v_{Rd}\right)i_d + \left[\left(v_{sq} - v_{Rq}\right)i_q\right]$. This power depends on the magnitude as well as the phase difference between the two voltages, namely v_S and v_R.

Since the reactive current is controlled to be zero, the expression of power transmitted reduces to the form, $p_C = \left(v_{sd} - v_{Rd}\right)i_d$

The third term $L\left(i_d\frac{di_d}{dt} + i_q\frac{di_q}{dt}\right)$ represents the instantaneous active power stored in the magnetic field. This power, in fact, comes out of the capacitor which in turn is transmitted to the inductor to give the instantaneous active power. This is justified by the term $\frac{di_d}{dt}$ which appears only during the transient conditions, not during the steady state power flow situations.

IV. P-Q CONTROL

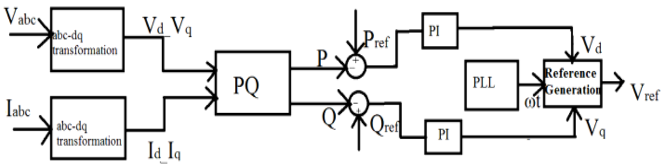
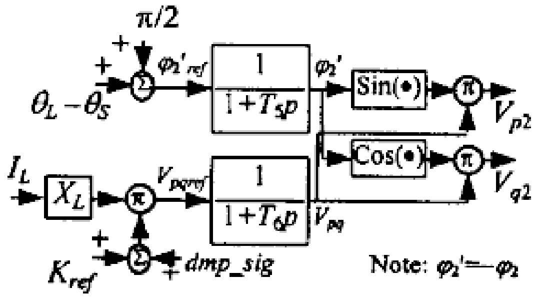


Fig. 3. P-Q Controller for Series Converter

The power flow control is adopted for series converter. For reducing the cross-coupling between the d- and q-constituents reference to the series converter, the control strategy adopted is basically the one including a decoupling term. The only addition to the control is a loop for eliminating phase unbalances on the line current, as shown in Fig 3. Unbalanced line currents are represented by the control system as negative-sequence components. These DC constituents are obtained by rotating the negative-sequence components in the opposite direction of the normal d-q transformation. A similar type of control, i.e. PI regulator plus decoupling terms, is adopted in order to force the measured negative-sequence components to zero [14]. As the positive- and negative-sequence circuit impedances are identical in the absence of motor loads, the same decoupling factor (Kd) can be employed for unbalance elimination. The only difference is a change in the sign of the contribution of the decoupling term because the d-q reference frame for the negative-sequence. In the end, the three-phase contributions from the power flow controller and from the unbalance elimination are added, forming thus the total voltage reference to be generated by the series converter [15]-[17]. A comparative study of two different controls, namely, phase angle controlled and vector controlled UPFC has been carried out in [19]. It is proved that damping controllers added to phase angle control performs better than vector control in mitigating the oscillations.

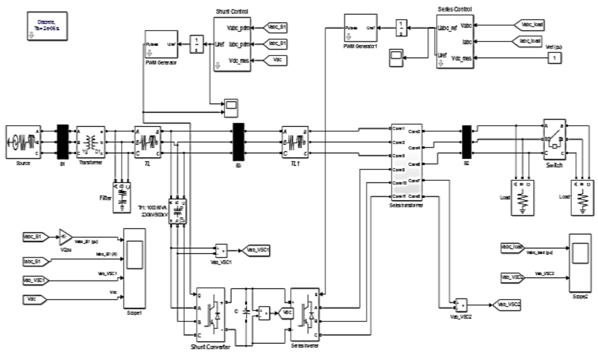
V. SERIES COMPENSATION CONTROL



4. Series Compensation controller

This utilizes the voltage inputs from the load side and line side along with the current line. In its simplest form, The line current I_L and the series converter terminal voltage V_T are determined together with the line frequency or the power flow, which can either be directly measured or calculated from the measurements of I_L and V_T. The desired reactance is set by a reactance reference, $Z_{R[}$ [18]. It for that reason makes a decision the amount of reactive reimbursement either capacitive or inductive added in the transmission line. The reference ZR of the reactance is modulated with bus frequency or line power indicators to generate the reference reactance, which while accelerated via the rms line cutting-edge IL to give the signal Vqr*. The sign Vdr* decides the importance of the collection injected voltage thing that may be either in section or out of phase with the road modern-day [18].

The two control schemes are combined and the series converter is controlled by a combination of these two control signals.



(1)

Fig. 5. Test System SIMULINK

As shown in Figure 5, circuit of the UPFC system connected to a source of short circuit level at 10MVA. The line voltage is 25kV. The 50kVA transformer feed to a transmission line whose entities are presented in table 1.

TABLE I. SYSTEM PARAMETERS

Name			Parameters
3 phase source			25KV, 10MVA
3 phase transformer			25kV/380V
Distributed parameter line			R=15ohms, L=2mH
UPFC Transformers	Shunt		10MVA,230/50kV
	Series		8MVA, 230/50kV
UPFC	Shunt	Power	Vrms(L-L)=218.1V f=50Hz, MVA=3.33MVA
		Control	Id control: Kp=0.45, Ki=30
	Series	Power	Vrms(L-L)=218.6V f=50Hz, MVA=3.33
		Control	Pref: Kp=0.045, Ki= 300 , Qcontrols, Kp=0.045 Ki=300
3 phase load1			10kW
3 phase load2			50kW
Capacitor			1800μF

VI. TEST RESULTS

Fig. 6 and 7 show the simulation results incorporating various control techniques for the series controller. It is seen that when we have a combination of controls, the performance of the UPFC by way of its controls is improved. Figure 7 represents the various voltages namely that of supply, converter 1 and capacitor and transmission line current where the conventional PQ controller along with line impedance control is used.

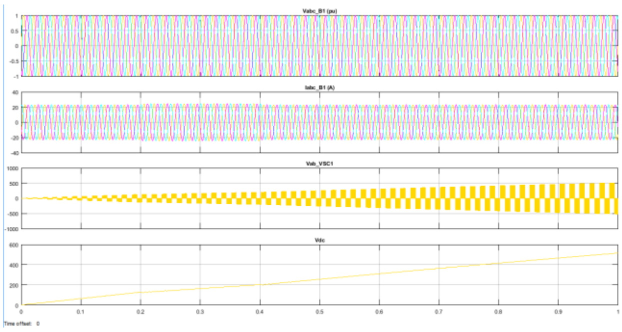


Fig. 6.a VSC1 & Vdc with PQ control

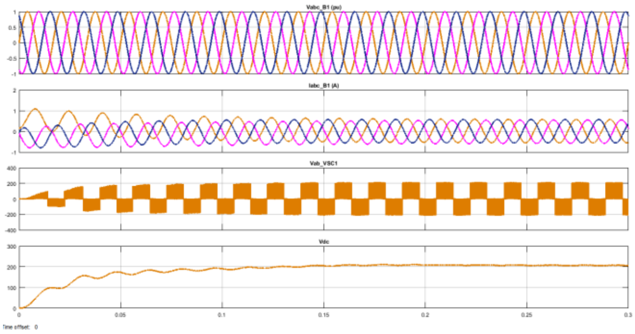


Fig.6.bV_{SC1} & Vdc with PQ and series compensation controls

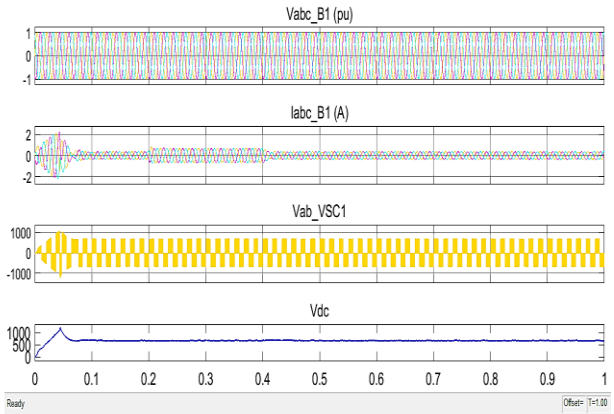


Fig. 7. VSC1 & Vdc with PQ control and impedance control

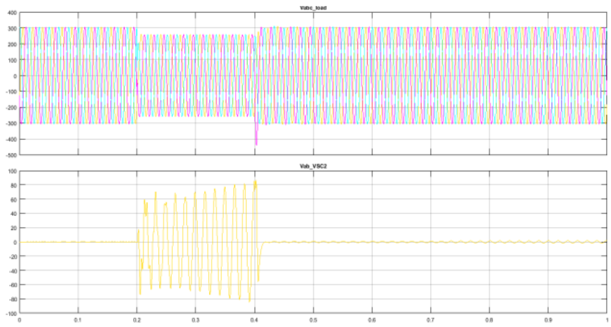


Fig.8. Vload &VSC2 with PQ control

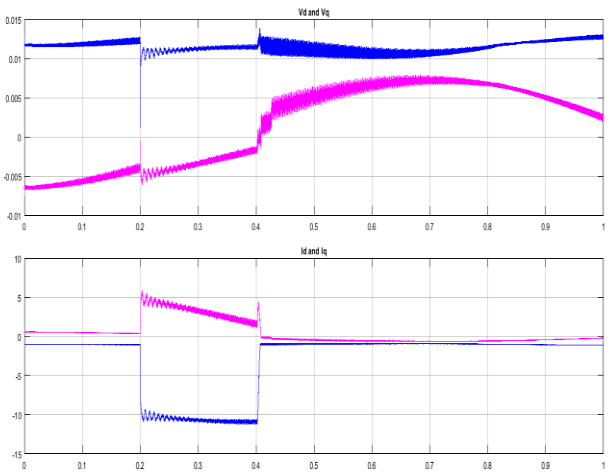


Fig.9. Vdref &Vqref waveforms

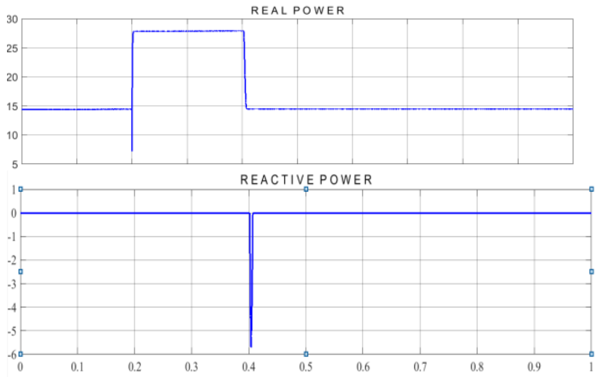


Fig.10. Real and Reactive power of the line

Figure 8 depicts the voltage injected by the UPFC for the duration of the fault. The reference voltages needed by the controllers are given in the figure 9. As shown in figure 10 when there is a fault in the system..

The circuit is modified and simulated for a 5 bus system. The switching devices used are IGBTs and the switching frequency employed is 100kHz. In the modified circuit of UPFC with 5 bus system, the transformers are selected to be of 20kV/230kV and all the performance examination done employing. The results are included in the tables II and III.

The power flows without controller and with individual controllers are tabulated below in table II.

TABLE II. SYSTEM BUS VOLTAGES

Voltage Bus	without UPFC	UPFC with (Voltages in p.u.)		
		PQ Compe-nsation	Series compe-nsation	PQ and series compe-nsation
B1	0.9903	0.9912	0.9668	0.9689
B2	0.9903	0.9912	0.9668	0.9689
B3	0.9825	0.9859	1.031	1.032
B4	0.9912	0.9931	0.9923	0.9939
B5	0.9912	0.9931	0.9923	0.9939

The performance of UPFC when connected to a 5- bus system is analyzed. The voltage profiles are found to be improved with better regulation in all the buses as shown in the above table.

The power flows in MW in all the buses at 5s are also found to be better as shown in table III.

TABLE III. POWERFLOW DATA

Bus No.	Without UPFC	UPFC with (Power in MW)		
		PQ Compensation	Series compe-nsation	PQ and series compensation
B1	-495.6	-340.4	-171.2	-181.6
B2	- 0.1727	159	335.3	320.3
B3	- 0.0160 6	153.7	398.3	416.3
B4	1472	1331	1172	1158
B5	1081	1095	1151	1145

VII. CONCLUSION

So far, the controllers for the UPFC were dealing with one method alone, employing control action; and in some cases PQ control is used; where as in this paper we use a combinational controller with PQ control and series compensation control methods. Here we are using the Pref and Qref values for PQ control. Along with this another control action is used which takes the angle δ, and uses source current to derive the series compensation control output. These two control signals are suitably joined to generate the triggering for the series converter. With this, it can be shown that the power flows have improved and better response is achieved.

From the simulation waveforms, we can see that the combinational control method provides better performance, which in turn helps in the overall improvement of power flow and dynamic performance of the transmission line. In future, the two methods can be combined with different weighing factors to optimize the performance.

References

1. Gyugyi L. (1991) *"A unified Power Flow Control Concept For Flexible AC Transmission Systems"*, Fifth International Conference on AC and DC Power Trans. IEEE, London:17–20.
2. Gyugyi L.(1993) *"Dynamic compensation of AC transmission lines by solid–state synchronous voltage sources"*, IEEE/PES. Vancouver Canada, 92:18–22.
3. Gyugyi L., Schauder C. D., Williams S. L., Rietman T. R.,Torgerson D. R., Edris E. (1994) *"The Unified Power Flow Controller: A New Approach to Power Transmission Control"*, IEEE/PES PWRD. San Francisco, CA: 24–28
4. Maryam Hashemi Namin(2006) *"Using UPFC in order to Power flow control"* IEEE
5. S.Limyingcharoen, U.D.Annakage, N.C.Pahalawaththa (1998) *"Effects of Unified power flow Controller' IEE proceedings-Generation, Transmission and Distribution*, Vol. 145, No.2: 182-188
6. K.R.Padiyar, A-M-Kulkarni, (1998) *"Control design and Simulations of Unified Power Flow Controller"*, IEEE transactions on Power Delivery, Vo1.13, 4.:1348- 1354

7. Hideaki Fujita, Yasuhiro Watanabe and Hirofumi Akagi (2001) *"Transient Analysis of a Unified Power Flow Controller and its Application to Design of the DC-Link Capacitor," IEEE* Power Electronics. *Trans.* Vol. 16, 5: 735–740
8. S.Kannan, Shesha Jayaram, M.M.A.Salama (2004) *"Real and Reactive power Coordination for a Unified Power Flow Controller," IEEE* Power Systems. *Trans.* Vol. 19, 3:1454–1461
9. Hideaki Fujita, Yasuhiro Watanabe and Hirofumi Akagi (1999) *"Control and Analysis of a Unified Power Flow Controller a," IEEE Power* Electronics. *Trans.* Vol. 14, 6: 1021–1027
10. Hideaki Fujita, Yasuhiro Watanabe and Hirofumi Akagi (1999*) "Control and Analysis of a Unified Power Flow Controller a," IEEE Power* Electronics. *Trans.* Vol. 14, 6: 1021–1027
11. Pengcheng Zhu, Liming Liu, Xiaoyuan Liu, Yong Kang and Jian Chen (2005) *"Analysis and Comparison of two Control Strategies for UPFC',* IEEE/PES Transmission and Distribution Conference & Exhibition
12. Fujita H.,Watanabe Y., Akagi H. (1998) *"Control and Analysis of a Unified Power Flow Controller",* IEEE Transactions on Power Electronics, 805–809
13. Padiyar K. R., Kulkarni, A. M. (1998) *"Control Design and Simulation of Unified Power Flow Controller",* IEEE Transactions on Power Delivery, Vol. 13, 4: 1348–1354
14. Dong L.Y., Zhang L., Crow M. L. (2002) *"A new control strategy for the unified power flow controller",* Power Engineering Society Winter Meeting, IEEE 1: 562– 566
15. Parvathy.S, K.C.Sindhu Thampatty, (2015) *"Dynamic Modelling and Control of UPFC for Power Flow Control"* Procedia Technology 21 Science Direct, 581 – 588
16. Y Zhang, H F Li, W J Du, Z Chen, H F Wang, S Q Bu, (2016) *"Coordinated damping control of phase angle controlled and vector controlled UPFC – a comparative study"* Proceedings of the International Conference on Unmanned Aircraft Systems (ICUAS)