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Application of vector control based methods for unified power flow controllers

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Abstract: In this paper a Unified Power Flow Controller (UPFC) model, based on a vector control theory including d –q rotating frame is introduced. At first control block diagrams of series and shunt UPFC inverter control schemes, based on d-q line currents are introduced. A heuristic simple vector control system for series UPFC inverter control scheme, based on real and reactive line powers is presented. The application of proposed method for investigating the performance of UPFC in power transmission lines is studied and simplicity and workability of the latter method in comparison to prior method is shown. Finally using different vector control strategies, simulation results of UPFC operation to control transmission line parameters, are presented.

Key-Words: AC transmission line, vector control, FACTS, UPFC, real power, reactive power

1 Introduction

Electric power flow through an alternating transmission system is a function of three basic parameters: transmission line impedance, voltage magnitude and phase angle. Traditionally in order to control the power flow of transmission systems, fixed capacitors and reactors were utilized. In recent years due to development of semiconductor devices, it is possible to control the flow of power by new power flow controllers entitled Flexible Alternating Current Transmission Systems (FACTS) which use solid state power electronic and switching converters. FACTS refer to those powers electronic systems such as thyristor controlled Series Capacitor (TCSC), Static Var Compensator (SVC), Static Synchronous Series Compensator (SSSC), Static Compensator (STATCOM), Phase Shifter (PS) and Unified Power Flow Controller (UPFC). A Unified Power Flow Controller is a power electronic system which can simultaneously provide VAR compensation, line impedance control and phase angle shifting [1, 2].The UPFC consists of two controlled power electronic converters which are connected together by a common DC link as illustrated in Fig. 1. Inverter 1 is connected in parallel with transmission line by transformer T1 whereas inverter 2 is connected in series with transmission line by transformer T2. Transformers T1 and T2 are used to isolate the UPFC and to match the voltage between the power system and series and shunt connected inverters. The real and reactive power flow in a transmission line can be controlled by back to back power electronic inverters illustrated in Fig. 1. The real and reactive power flows in a transmission line can be quickly regulated by changing the magnitude and phase angle of the injected voltage produced by series connected inverter. The second inverter prilimarily provides the real power required by series connected inverter from the common DC link, but it can also operate as an independent reactive compensator.Therefore the UPFC can control the flow of real and reactive power in the transmission line.

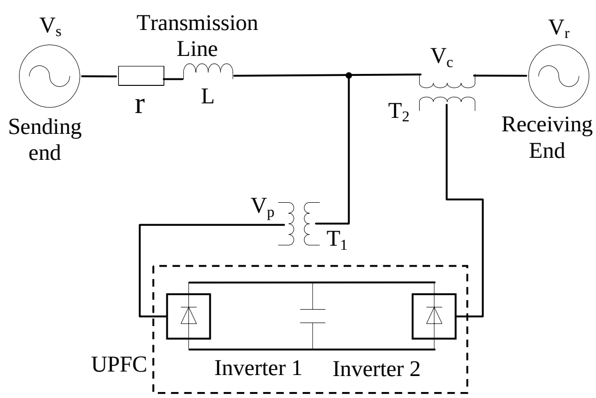

Fig 1. UPFC system connected to transmission system

Several studies have been implemented to show the performance of UPFC system in steady state conditions. Some of these studies propose a control system for UPFC which are based on the principle that the real power varies with phase angle whereas the reactive power is influenced by voltage magnitude [3].Therefore to control the real power flow in the transmission line, the phase angle of series compensation voltage is adjusted while to regulate the reactive power flow, the amplitude of the series voltage is controlled, but as shown in Ref [3], the real and reactive power flows in the transmission line are influenced by both the amplitude and the phase angle of series compensation voltage, therefore the change in real power can significantly effect the level of reactive power flow and it will be an interaction between the real and reactive power flows. To improve the performance and reduce the interaction between the real and reactive power flows a control system for UPFC, based on d-q axis theory was presented [4], but only UPFC s series controller was investigated.
In this paper a vector control based method for modeling of a complete UPFC is developed. The control blocks of UPFC series and shunt control schemes, based on d-q line currents are presented individually and then a heuristic simple vector control method, based on real and reactive line powers is proposed. The simplicity and workability of the latter method in comparison to former one is shown, finally using different vector control strategies, the simulation results of performance a typical UPFC to control transmission line parameters, are presented.

2. Modeling and analysis of UPFC system

Vector control has long been used in electrical machine analysis and is now being applied more widely to electrical power system analysis and control. In this analysis instantaneous three phase variables are converted to d-q axis components in a synchronous rotating two axis system and therefore order of the system is reduced and calculation are less complicated [5] The equivalent circuit of a UPFC system is shown in Fig. 2, where the series and shunt inverters are represented by voltage sources v_c and v_p respectively. The transmission line is modeled as a series combination of resistance, r, and inductance L, whereas the parameters r_p and L_p represent the resistance and leakage inductance of shunt transform respectively.

Some nonlinear parameters such as GTO switching and transformer saturation are neglected in this study.

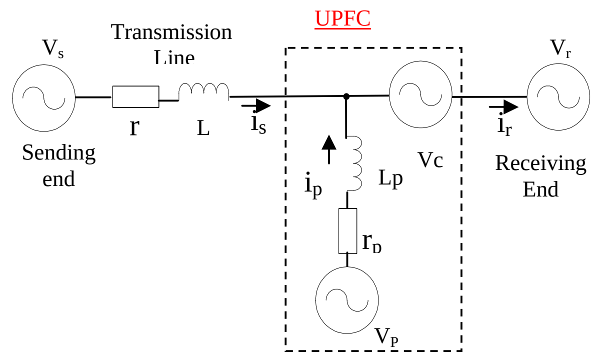

Fig 2. Equivalent circuit of a UPFC system

2.1 Modeling of series UPFC control system

In Fig. 2, considering only the series part of UPFC, the mathematical model of UPFC in three phase system can be derived as Eq. (1)

$$\frac{di_r}{dt} = \frac{-r}{L} i_r + \frac{1}{L}(v_s - v_c - v_r) \qquad (1)$$

Using d-q transformation equations as illustrated in Eqs (2)-(4).
The above three phase series UPFC model can be rewritten in form of two axis d-q system as given by Eqs (5), (6)

$$[T]\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (2)$$

Where:

$$[T] = \frac{2}{3}\begin{bmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin(\theta) & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (3)$$

and

$$\theta = \tan^{-1}(\frac{i_q}{i_d}) \qquad (4)$$

$$\frac{di_{rd}}{dt} = \omega . i_{rq} - \frac{r}{L}.i_{rd} + \frac{1}{L}\left(v_{sd} - v_{cd} - v_{rd}\right) \quad (5)$$

$$\frac{di_{rq}}{dt} = -\omega . i_{rd} - \frac{r}{L}.i_{rq} + \frac{1}{L}\left(v_{sq} - v_{cq} - v_{rq}\right) \quad (6)$$

From the instantaneous power theory derived by Akagi [6] the instantaneous real and reactive powers at the receiving – ends are given by Eqs. (7), (8)

$$P_r = \frac{3}{2}\left(v_{rd}.\ \ i_{rd} + v_{rq}.\ \ i_{rq}\right) \qquad (7)$$

$$Q_r = \frac{3}{2}\left(v_{rd}\ \ .i_{rq} - v_{rq.}\ \ i_{rd}\right) \qquad (8)$$

Where

$$i_{rd} = i_{sd} + i_{pd} \qquad (9)$$

$$i_{rq} = i_{sq} + i_{pq} \qquad (10)$$

In order to control the real and reactive power flows in such a transmission system, the reference values for desired real and reactive power flows are necessary as the inputs to UPFC control system. By rearranging Eqs.(7), (8), using the real and reactive power references at the receiving end P_{ref} and Q_{ref}, the receiving end line current references are as Eqs (11),(12)

$$i_{rdref} = \frac{2}{3}.\frac{\left(P_{ref}.v_{rd} - Q_{ref}.v_{rq}\right)}{v_{rd}^{\ 2} + v_{rq}^{\ 2}} \qquad (11)$$

$$i_{rqref} = \frac{2}{3}.\frac{\left(P_{ref}.v_{rq} + Q_{ref}.v_{rd}\right)}{v_{rd}^{\ 2} + v_{rq}^{\ 2}} \qquad (12)$$

In order to control real and reactive power levels at the receiving end the actual transmission line currents i_{rd} , i_{rq} should be compared to their reference values , deducted from desired values of P_{ref} and Q_{ref} . Fiq.3 shows the block diagram of the series UPFC control system, based on d-q line currents.

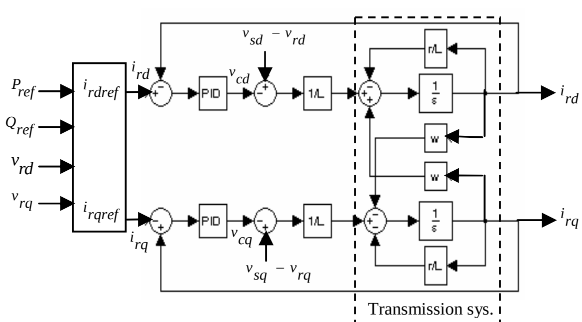

Fig 3. UPFC series control system based on line currents

In Fig .3 the actual receiving end line currents i_{rd} and i_{rq} are calculated from Eqs. (5), (6) and compared to the current references i_{rdref} and i_{rqref} calculated from Eqs. (11), (12). The resulting current errors are then processed by two Proportional Integral (PI) Controllers to obtain the d-q series injected voltages, v_{cd} and v_{cq} .

These voltages as well as sending and receiving end voltages are applied to transmission system model to determine the actual receiving line currents.

2.2 Modeling of shunt UPFC control system

Similar to mathematical model of series UPFC system, considering only the shunt part of UPFC in Fig. 2 the model of UPFC in three phase system can be derived as Eq. (13).

$$\frac{di_p}{dt} = \frac{-r_p}{L_p} i_p + \frac{1}{L_p}\left(v_s - v_p\right) \qquad (13)$$

Similarly applying d-q transformation equations, the above three phase shunt UPFC model can be rewritten in form of two axis d-q systems as given by Eqs. (14), (15)

$$\frac{di_{pd}}{dt} = \omega.i_{pq} - \frac{r_p}{L_p}.i_{pd} + \frac{1}{L_p}\left(v_{sd} - v_{pd}\right) \quad (14)$$

$$\frac{di_{pq}}{dt} = -\omega.i_{pd} - \frac{r_p}{L_p}.i_{pd}.+\frac{1}{L_p}\left(v_{sq} - v_{pq}\right) \quad (15)$$

Shunt inverter supplies the real power required by the series inverter as well as being capable of providing reactive power to the system.

Theoretically it is assumed that the power flowing at the sending end is completely delivered to the receiving end, however in a real system there will be power losses in the transmission line and the UPFC system. Therefore the sending end power reference P_{sref} is determined from receiving end power reference, P_{rref} plus system losses P_{loss} . As illustrated in Fig.1 the DC bus voltage is used to determine the system loss. Here again similar to Eqs. (11) and (12) the combination of sending end active and reactive power references P_{sref} and Q_{sref} as well as d-q sending end voltages are used to calculate the sending end line current references i_{sdref} and i_{sqref} .

Fig. 4 shows the block diagram of the shunt UPFC control system, based on d-q line current.

The current references for shunt inverter i_{pdref} and i_{pqref} are determined from subtraction of receiving and sending end current references as obtained in Eqs. (9) and (10). The error between the shunt reference currents, i_{pdref} and i_{pqref} and the actual shunt currents, i_{pd} and i_{pq} are then used by the two PI controllers to produce the d-q shunt injected voltages, v_{pd} and v_{pq}. Similar to series UPFC control system these voltages are applied to transmission system model to determine the actual injected shunt currents.

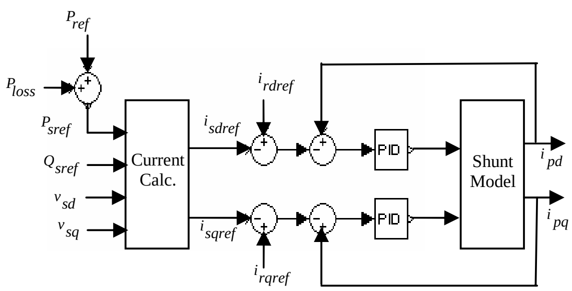

Fig 4. UPFC shunt control system

2.3 Modeling of heuristic simple series UPFC control System

Referring to prior series UPFC control system depicted in Fig.3 and Eqs.(5) and(6), it is observed that there are some couplings between d and q current loops , i_{rd} and i_{rq} (due to $\omega.i_{rq}$ and $\omega.i_{rd}$ expressions in Eqs (5) and (6) , respectively) , therefore there will be an almost big interactions between two output real and reactive power flows delivered at the transmission receiving end .

In order to avoid these interactions and get better responses, a heuristic vector control based model for series UPFC control system is proposed that is based on real and reactive line power flows, instead of d-q line currents. Considering Fig. 2, the receiving end line current in d-q axis model is as described in Eq. (16)

$$i_r = \frac{(v_{sd} + jv_{sq}) - (v_{cd} + jv_{cq}) - (v_{rd} + jv_{rq})}{jx} \quad (16)$$

Taking into account receiving end voltage (v_{rd} + jv_{rq}) and line current, real and reactive power flows at the transmission receiving end can be derived as Eqs. (17), (18)

$$P = \frac{1}{x}\left[v_{rd}(v_{sq} - v_{cq} - v_{rq}) - v_{rq}(v_{sd} - v_{cd} - v_{rd})\right] \quad (17)$$

$$Q = \frac{1}{x}\left[v_{rq}(v_{sq} - v_{cq} - v_{rq}) + v_{rd}(v_{cd} - v_{cd} - v_{rd})\right] \quad (18)$$

Where: x= r+j ω L

According to Eqs (5) and (6) for ω L>>r in steady state condition, i_{rd} and i_{rq} are proportional to v_{cq} and v_{cd} , respectively [7].

Assuming small difference between sending end receiving end voltage phase angles and from Eqs. (18) and (19) , it is concluded that receiving end real and reactive power flows are proportional to v_{cq} and v_{cd} , respectively , but in fact referring to Eqs. (17) and (18) due to common terms in above equations there will be still interactions between output real and reactive power flows. The block diagram of proposed power based control system for UPFC series branch is depicted in Fig. 5.As illustrated, the measured real and reactive powers are calculated and compared to the reference values to produce error signals. These error signals are processed by PI controllers to regulate v_{cq} and v_{cd}. Using PLL output and by inverse d-q transformation, UPFC series injected voltage is derived. Comparing two series UPFC control systems depicted in Figures 3 and 5, it can be seem that the heuristic power based control system is simpler than the former current based control one. In addition, due to control system configuration depicted in Fig.5, there will be lower interactions between real and reactive output power flows.

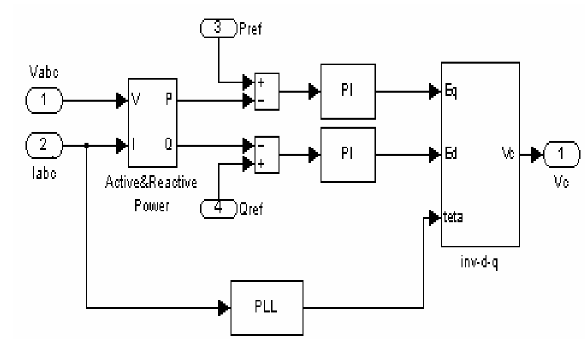

Fig 5. Heuristic UPFC series control system based on line power flows

3 Simulation results

In this section in order to investigate the performance of a UPFC to control the power system parameters, the simulation results of employing a typical UPFC in transmission line are presented. MATLAB / SIMULINK software program is used for computer simulation. For each of the control system mentioned above, a simulation model is created. The parameters of UPFC series and shunt inverters as well as transmission line are listed in Table 1

Table 1: The Parameters of transmission system and UPFC model.

v_r	v_s	r	L	r_p	L_p	c
$220v$	$220v$	0.8Ω	$10mH$	0.4Ω	$10mH$	$2000\mu F$

Figures 6 and 7 show the response of a UPFC with current based series control system described in section 2-1 and defined shunt control system, to the changes in reference receiving end real and reactive power flows at t= 0.2 sec, respectively. As illustrated there are almost big interactions between two output produced receiving end real and reactive power flows, due to couplings between d and q receiving end current loops.

Similarly Figures 8 and 9 show the response of a UPFC with heuristic simple power based series control system, described in section 2-3 and former shunt control system, to the same changes in reference receiving end real and reactive power flows.

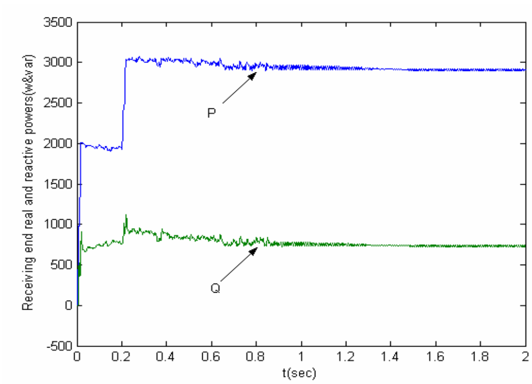

Fig 6.Current based control response of UPFC to step change in active power

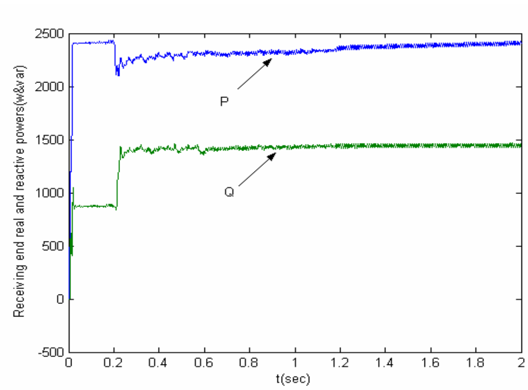

Fig 7. Current based control response of UPFC to step change in reactive power

Considering these figures and comparing with figures 6 and 7, it is clearly deduced that due to simplicity and lower couplings in proposed heuristic series controller, the interactions between real reactive output powers will be decreased.

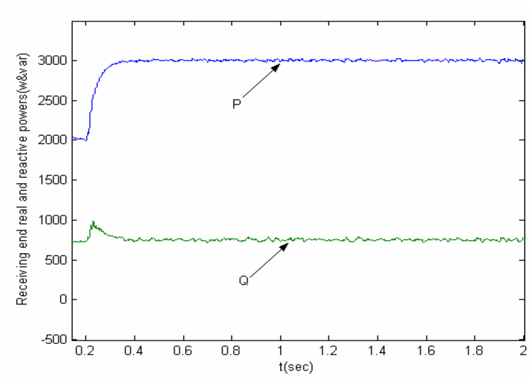

Fig 8. Power based control response of UPFC to step change in active power

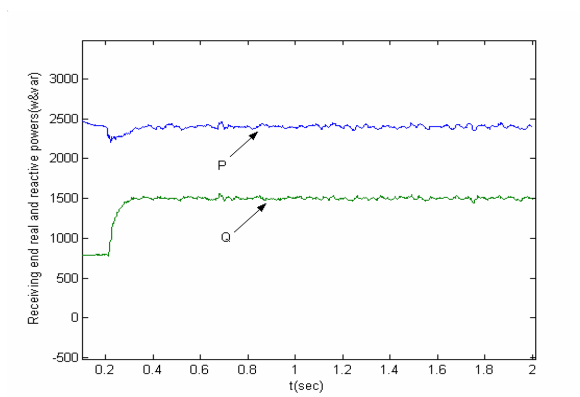

Fig 9. Power based control response of UPFC to step change in reactive power

According to step changes in receiving end real and reactive powers, figures 10 and 11 show the variation of receiving end current as well as series UPFC injected voltages, due to these changes, respectively.

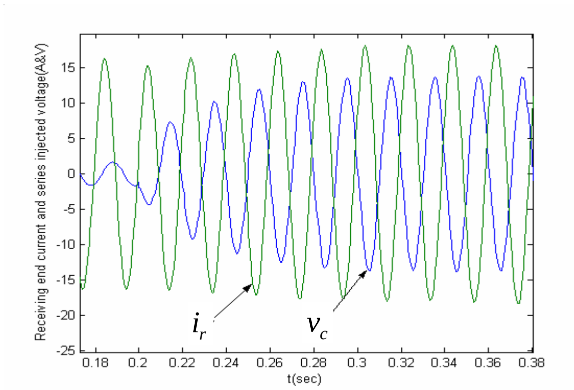

Fig10. Effect of increasing real power on injected voltage and line current

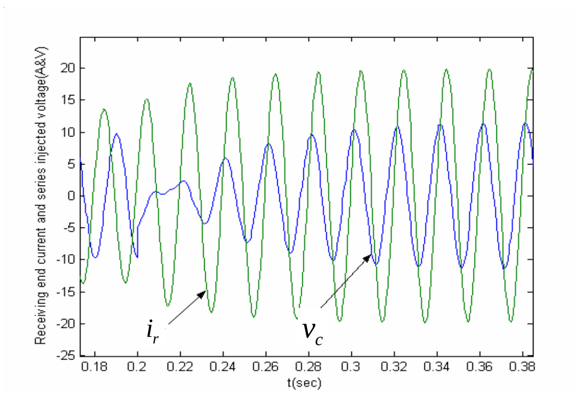

Fig 11. Effect of increasing reactive power on injected voltage and line current

From Fig. 11, it is clearly observed that for only change in real power the injected voltage remains in quadrature with line current.It is also observed from Fig .12 that for only change in reactive power, the injected voltage remains in phase with line current. Finally as illustrated in figures 11 and 12, it is appear that magnitudes of receiving line currents are affected proportional to both real and reactive power variations, but as shown in Fig .12, in case of only change in reactive power, the receiving end line current is not so affected in comparison to only change in real power, as illustrated in Fig. 11.

4 Conclusion

The application of vector control theory to investigate the performance of UPFC system was presented. The block diagrams of series and shunt UPFC control systems were investigated individually to study its operation in steady state conditions. A control system based on transmission line currents and a heuristic simple control system based on receiving end real and reactive line power flows were presented for series UPFC control system. The application of UPFC with proposed, power flow based, series control system was investigated and its accuracy and workability with respect to former model was shown. Finally the simulation results of a typical UPFC to control the real and reactive power flows as well as other transmission system parameters were presented.

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