P-Q Decoupled Control Scheme Using Fuzzy Logic Control for the Unified Power Flow Controller

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***Abstract* – This paper presents a Watt-Var decoupled control scheme using a PI fuzzy logic regulator for the Unified Power Flow Controller to improve the control performance of power system and reduce the inevitable interactions between the real and reactive power flow control parameters. To simplify the theorical analysis of the control system the 3-phase description of two-bus test power system model embedded with a UPFC is transformed into d-q components based on a synchronously rotating reference frame. Comprehensive simulation results on MATLAB program are presented and discussed to verify the effectiveness of the proposed control scheme.**

Keywords – DTC, Induction Motor, FFT, Modelling

I. INTRODUCTION

The flexible AC Transmission Systems (FACTS) based on power electronics offer an opportunity to enhance controllability, stability, and power transfer capability of AC transmission system [1,2].

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 and providing voltage support [2].

The UPFC is consisted of two dc/ac inverters, one, defined as Static Synchronous Compensator (STATCOM), connected in shunt with the line through a transformer and the other one defined as Static Series Compensator (SSSC), connected in series with the transmission line through a series insertion transformer Fig.1. The dc terminals of the two inverters are connected together and their common dc voltage is supported by a capacitor bank [7, 9], to allow the bidirectional flow of real power between the series terminals of the SSSC and shunt terminals of the STATCOM. The real power exchange by the SSSC is obtained from the transmission line via the shunt controller; the latter is also used for voltage control by injecting reactive power. So the UPFC can control real and reactive power as well as transmission line voltage control Fig.1.

II. OPERATING FUNCTION OF UPFC

In order to study UPFC characteristics, the development of UPFC power flow models is fundamentally important. Significant progress has been made during the past few years.

Among existing steady-state models, the decoupled model has been adopted for many power flow programs [1, 8]. Unfortunately, this model completely neglects active power losses of coupling transformers. Also, it is only applicable when voltage magnitude, active power, and reactive power are controlled simultaneously

In this paper, the UPFC is described as well as its dynamic and steady state models. The whole system power source utility and the UPFC, is modelled using a modal transformation (Park). A conventional controller proposed in [7] and [8], is explained. This strategy is known as: decoupling control. The model has been developed with MATLAB-SIMULINK simulation program.

A circuit equivalent of the UPFC within two front end voltage sources connected by a single transmission line is shown in Fig.2, and a phasor diagram including the UPFC operation is shown in Fig.3, if the UPFC is positioned at sending-end bus S. One can consider the UPFC as a synchronous ac voltage source V_{se} [1, 3]. So, the series transformer injects a voltage in series with the transmission line [2, 9]:

$$\left|V_{se}\right| \Rightarrow 0 \le \left|V_{se}\right| \le V_{se}^{max}$$
$$\bar{V}_{se} \Rightarrow 0 \le \varphi_{se} \le 360^{\circ} \quad , \qquad (1)$$

The SSSC provides this variable voltage both in magnitude and angle phase. If the operation of the SSSC converter is under a PWM technique, its modulation index is varied so that the desired magnitude and angle phase is obtained within the operating zone described in (1).

For a V_{se} leading or lagging (± 90o) with respect to the transmission line current, the converter exchanges (generates or absorbs) only reactive power with the line, a particular UPFC operation met also by the SSSC operating by itself. In this case, the SSSC is operating at zero power factor and it behaves like an inductive (+90) or capacitive (-90) reactance. For any other operating condition of V_{se} in magnitude and phase, it is clear that the STATCOM (shunt converter) is essential to maintain the DC link voltage and to provide the real power exchange by the SSSC with the line [2].

The STATCOM also operates under a Pulse Width Modulation Technique (PWM). Although its basic function is to provide or absorb the real power demanded by the SSSC at the common DC link to support the real power exchange resulting from the series voltage injection, it can provide shunt reactive compensation. The real power is taken from the ac means through a shunt power transformer, and it is provided in this case by the sending-end bus S. Like the above controller, it may operate at any power factor, from unity to zero. It can be observed that there is no possibility to exchange reactive power through the DC link, so both controllers absorb or generate reactive power independently of each other.

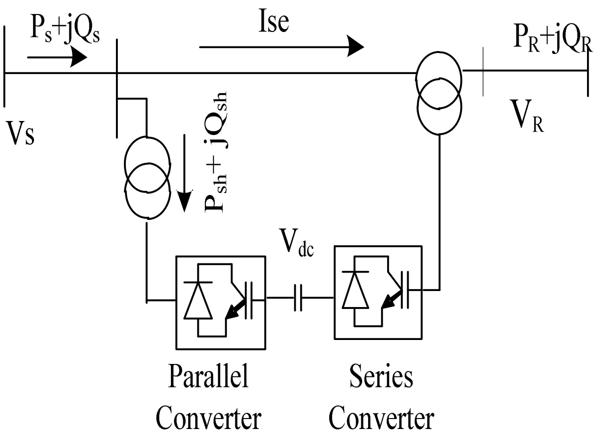


Fig.1 Implementation of the UPFC

There is a possibility to obtain a simplified model of the system shown in Fig.2. The balanced three-phase system of voltages and currents can be transformed into a synchronously-rotating orthogonal system by using a modal transformation (Park) [6, 7].

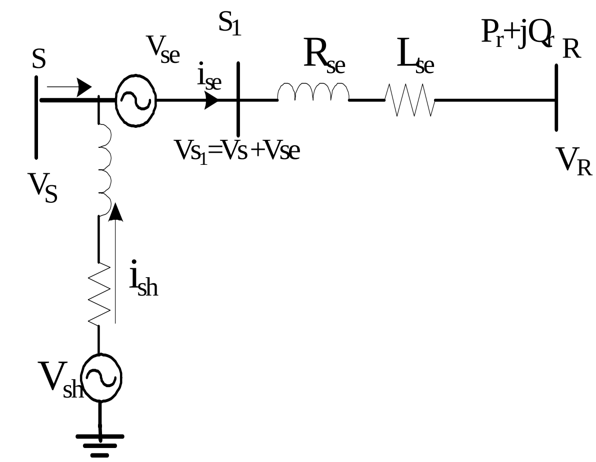


Fig. 2 Single-phase representation of three-phase UPFC system.

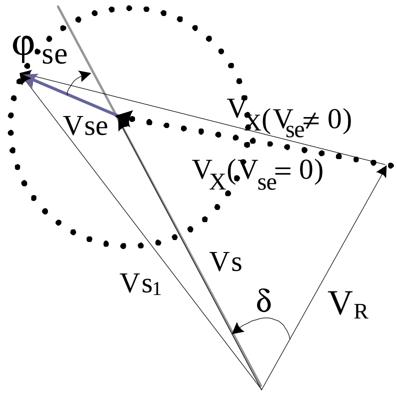


Fig. 3 Phasor diagram of the UPFC operating system.

III. MODELLING OF THE UPFC

The Fig.2 represents the equivalent circuit of a UPFC, the series and shunt converters can be rated ideal sources V_{se} and V_{sh} respectively.

The transmission line is modelled as a series combination of resistance R_{se} and inductance L_{se}. The non-linearity caused by the semiconductor devices, transformer saturation and controller time delays are neglected in the equivalent circuit and it is assumed that the transmission system is symmetrical.

The following per-unit system [8, 5] has been adopted (2)

$$i_x' = \frac{i_x}{i_B};\; v_x' = \frac{v_x}{v_B};\; Z_B = \frac{v_B}{i_B}$$
$$L_x' = \frac{\omega_B L}{Z_B};\; \mathrm{R}' = \frac{R}{Z_B}$$
$$x = a, b, c \tag{2}$$

By performing d-q transformation, the current through the transmission line can be described by the following equation in [4, 6].

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{se}}{L_{se}} & \omega \\ -\omega & -\frac{R_{se}}{L_{se}} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} -\frac{\omega_B}{L_{se}} & 0 \\ 0 & -\frac{\omega_B}{L_{se}} \end{bmatrix}\begin{bmatrix} V_{sed} \\ V_{seq} \end{bmatrix} \tag{3}$$

Where: subscripts d and q denotes the Park components of the currents and voltages.

Where: ω_b : is the base frequency

And ω : synchronous rotating system frequency

Both components of the current are cross-coupled through the term ω .

Similarly, the shunt inverter can be described by:

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{sh}}{L_{sh}} & \omega \\ -\omega & -\frac{R_{sh}}{L_{sh}} \end{bmatrix}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \begin{bmatrix} -\frac{\omega_B}{L_{sh}} & 0 \\ 0 & -\frac{\omega_B}{L_{sh}} \end{bmatrix}\begin{bmatrix} V_{shd} \\ V_{shq} \end{bmatrix} \tag{4}$$

The common connection between the two converters is formed by a dc-voltage bus. A dc-voltage controller can regulate the active power flow between the two converters and maintain the required voltage level across capacitor.

$$\frac{1}{2} C \frac{d}{dt} V_{DC}^{2} = P_{se} - P_{sh} \tag{5}$$

Where:

C: is the dc-circuit capacity

VDC: dc-voltage

P_{se}: Active power absorbed by the series inverter

P_{sh}: Active power delivered by the shunt inverter

Equation (5) in the synchronous dq-frame can be written as:

$$\frac{dV_{dc}}{dt} = \frac{3}{2CV_{dc}}(V_{sed}I_{Rd} + V_{seq}I_{Rq} - V_{shd}I_{shd} - V_{shq}I_{shq}) \tag{6}$$

Where

$$i_{Rd} = i_{sd} + i_{shd}$$
$$i_{Rq} = i_{sq} + i_{shq} \tag{7}$$

Fig.4 illustrates the dc-voltage control scheme. By sensing and filtering the voltage across the capacitor and comparing it to the optimal reference voltage V^*_{dc}, the dc voltage error can be obtained.

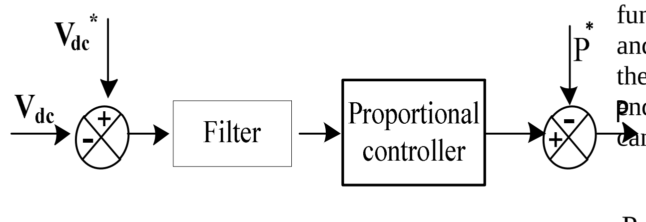


Fig.4 DC-voltage control system.

IV. PI DECOUPLING CONTROL

The principle of this control strategy is to convert the measured three phase currents and voltages [3, 8], as is illustrated in Fig.5.

The power control is then realized by using properly deigned controllers to force the line currents to follow their references. With reference to equations (3) and (4), the interaction between the current loops is caused by the ωL coupling term. Decoupling is achieved by feeding back this terms and subscripting [6, 8].

In Fig.5 is represented the PI-based decoupling control system for the UPFC.

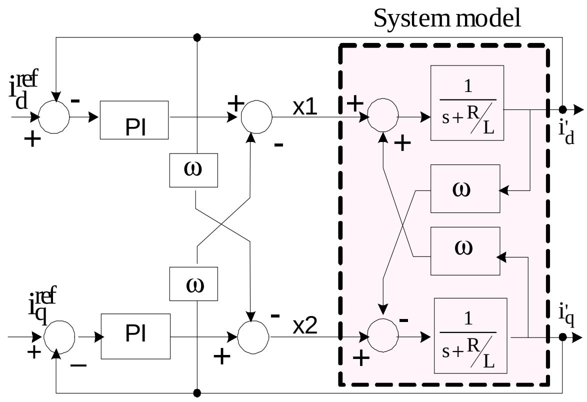


Fig.5 PI decoupling control system.

The shunt converter mainly supplies the active power demand of the series converter. It can also exchange reactive power with reactive power with the system to support voltage at the coupling point but this capability is not explored in this study.

The shunt converter has the capability of independently controlling the shunt real and reactive power components. The shunt reactive current is regulated to maintain the transmission line voltage reference value at the point of connection. The shunt real power is dictated by the DC link, thereby providing the real power needed by the series voltage injection.

The block diagram of the overall UPFC control system is shown in Fig.6. the state references r, controls u, and outputs y of the UPFC control system are $[i^*_{sed}, i^*_{seq}, i^*_{shd}, i^*_{shq}]^T$, $[V_{sed}, V_{seq}, V_{shd}, V_{shq}]^T$, $[i_{sed}, i_{seq}, i_{shd}, i_{shq}]^T$ respectively. The function of the controller is to control the active (Pr) and reactive (Qr) power flow at the receiving end of the of the line of Fig.1. Using the values of receiving-end voltage and line (or series converter), Pr and Qr can be written as:

$$P_r = \frac{3}{2}(V_{Rd}i_{sed} + V_{Rq}i_{seq})$$
$$Q_r = \frac{3}{2}(-V_{Rd}i_{seq} + V_{Rq}i_{sed}) \tag{8}$$

When the active and reactive power references (P^*_r and Q^*_r) are known, the corresponding direct and quadrature axes current references of the series converter (i^*_{sed} and i^*_{seq}) can easily be determined by (9)

$$i_{sd}^{*} = \frac{2}{3}\frac{(p_s^{*}v_{sd} - q_s^{*}v_{sq})}{v_{sd}^{2} + v_{sq}^{2}} ,$$
$$i_{sq}^{*} = \frac{2}{3}\frac{(p_s^{*}v_{sq} - q_s^{*}v_{sd})}{v_{sd}^{2} + v_{sq}^{2}} \qquad (9)$$

Where the * subscript defines the reference quantities.

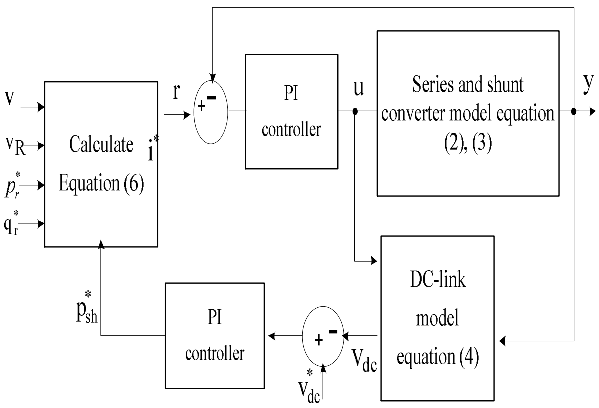


Fig.6 the block diagram of the overall UPFC control system.

V. FUZZY MATRIX CONTROLLER

Fuzzy logic is close in sprit to human thinking and natural language than other logical systems. It provides an effective means of capturing the approximate and inexact nature of systems [8], [9].the fuzzy logic controller based on fuzzy logic provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy [8].

As the UPFC models are complex to derive, non-linear equations are involved and equipment has a wide range of operation, it is reasonable to thin on a control strategy that could be based on a model-free approach. T handle the subjectivity associated with the model, one can use a fuzzy logic controller.

The basic architecture of a PI fuzzy logic controller is presented in fig.6.in this paper the kernel of the control is substitute the conventional controllers explained in section III. By the nearest corresponding fuzzy version; i.e. a proportional classic controller is substituted by a proportional fuzzy control. This is done to maintain the simplicity and for comparing the overall performance of the fuzzy controller against its conventional version.

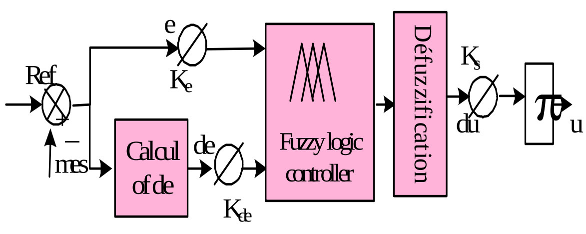


Fig.8 PI fuzzy logic controller.

Where e is the system error and du is the increment of control. The parameters Ke, and Kde are chosen according to the predicates associated to e and de. Ks is the integral gain.

The membership functions for input and ouput are represented in Fig.7 and Fig.8 respectively.

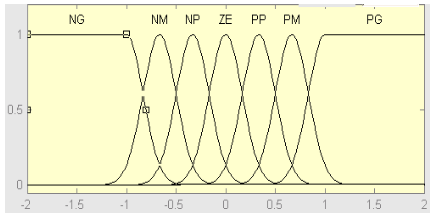


Fig.7 membership functions of e and de.

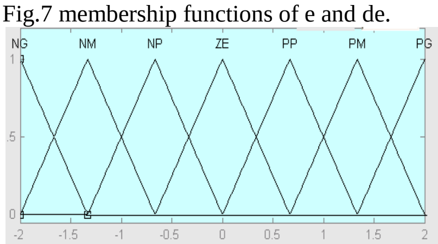


Fig.8. membership functions of du.

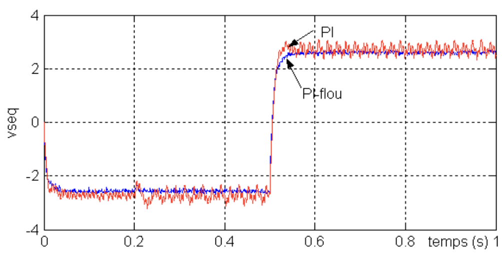
The decoupling strategy is performed by the rule base matrix given by table 1

TABLE I
TABLE 1REPRESENTATION OF THE INFERENCE RULES

de \ e	Ng	Nm	Np	Ez	Pp	Pm	Pg
Ng	Ng	Ng	Ng	Ng	Nm	Nm	Ez
Nm	Ng	Ng	Ng	Nm	Np	Ez	Pp
Np	Ng	Ng	Nm	Np	Ez	Pp	Pm
Ez	Ng	Nm	Np	Ez	Pp	Pm	Pg
Pp	Nm	Np	Ez	Pp	Pm	Pg	Pg
Pm	Np	Ez	Pp	Pm	Pg	Pg	Pg
Pg	Ez	Pp	Pm	Pg	Pg	Pg	Pg

V. SIMULATION RESULTS

The derived basic control of the UPFC was tested in Matlab code. The performance of the proposed PI controllers is evaluated through digital simulations. The traces of some characteristic values of the series and parallel UPFC branch are represented in Fig.9.



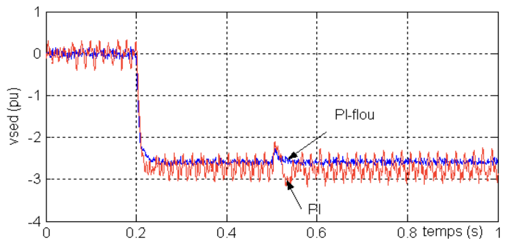


Fig.9 sending- end voltage response under PI and fuzzy PI regulator.

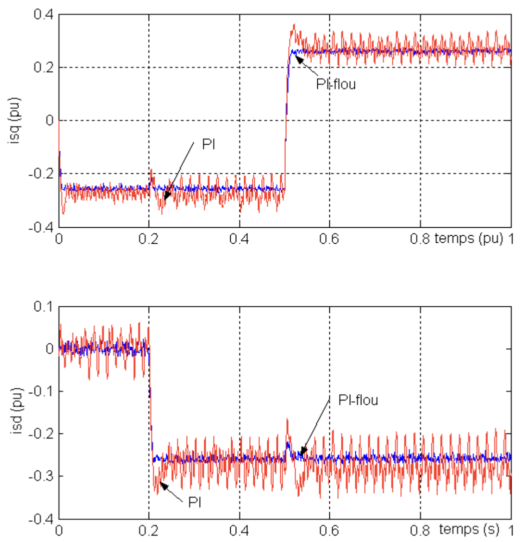


Fig.10 sending- end current response.

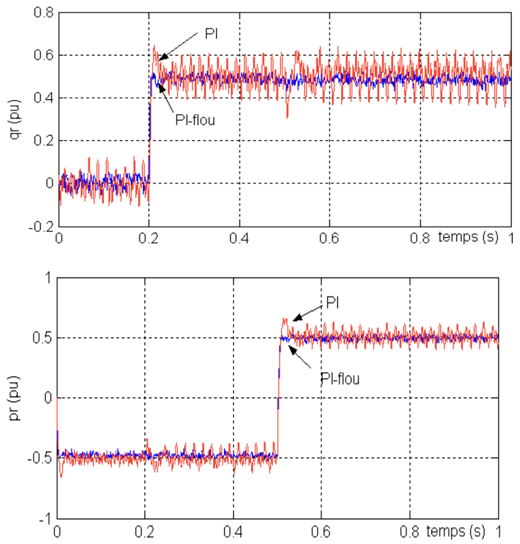


Fig.11 sending- end voltage response under PI and fuzzy PI regulator.

During simulation, the active power exchange between the series branch and the system is compensated by active power exchange of the parallel branch, which, using the dc control system also makes it possible to maintain the dc-voltage at the specified voltage.

IV. CONCLUSION

This paper deals with the mathematical modelling and decoupled Watt-Var control algorithm applied to the UPFC system. In this scheme a coordination control strategy is applied to the shunt converter of the UPFC, and a decoupling power flow control scheme is applied to the series converter of the UPFC.

Simulation results present the effectiveness of the control scheme. With this control strategy the UPFC can have fast power flow control ability with constant dc link capacitor voltage and stable UUPFC bus voltage.

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