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Control algorithms for control of real and reactive power flows and power oscillation damping using UPFC

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ABSTRACT

This paper investigates the application of multivariable control technique to multi-input multi-output (MIMO) non-linear problem of a power transmission system with UPFC. The main objective is to achieve effective independent control of real and reactive power flows with zero dynamic interactions. Towards achieving the objective, feed-back linearization control (FBLC) scheme is implemented in the laboratory for the control of UPFC. A two-bus power system with UPFC has been built in laboratory and the control implementation has been carried out using DSP TMS320LF2407A. Both power flow control and power oscillation damping issues are addressed. The excellent correlation between simulation and experimental results using a laboratory test system establish the validity of the proposed scheme. Although the power stage of the developed laboratory system is a scaled down model and has limited ratings, the FBLC controller can be used equally effectively in a more realistic system set up by appropriate scaling factors for the fed-back signals of currents and voltages and for initiating the inverter voltages. The proposed controller enables UPFC to independently control the real and reactive power with absolute decoupling. Also it is found that the overall performance of the system with the proposed controller is far superior to that using conventional cascade PI control structure.

1. Introduction

In the recent years UPFC has been proposed in the field of power transmission to increase power flow as well as an aid for improving the system stability. UPFC is one of the most important FACTS devices since it can provide various types of compensation, i.e., voltage regulation, phase shifting regulation, impedance compensation and reactive compensation. The unique feature of UPFC is its capability for independent control of real and reactive power flows in the transmission system.

The UPFC is implemented practically using two solid state voltage source converters (shunt compensation block and series compensation block) which are connected to a common DC link capacitor and each converter is coupled to the ac line through a transformer as shown in Fig. 1.

The steady state characteristics and performance of a UPFC have been widely reported in literature [1,2]. Many research articles [3–6] have been reported in the area of controllers for UPFC. Commonly the schemes are based on PI control and include an inner voltage loop and an outer current loop. Such a cascade control structure is not effective for the multi-variable UPFC system wherein the interaction among the controlled variables is severe. In general, the PI control-based techniques are easy to implement, simple and reasonably effective. But the performance with PI-based controllers widely varies with respect to the operating points. Further, the control of UPFC based on the conventional PI control strategy is prone to severe dynamic interaction between real and reactive power flows [6–9]. In this context, non-linear techniques offer a new perspective for achieving better dynamics and control. For instance, by adding appropriate feed-back, the overall system can be rendered linear and thereby linear control techniques can be applied effectively. Although considerable research work in this area has concentrated on developing control strategies using computer simulations, there is a general lack of experimental verification of many of the proposed controls. Since the focus of this study is to experimentally verify the control implementation, a two-bus power system is chosen for investigations.

This paper presents the details of implementation of feed-back linearization approach in a scaled down laboratory set up. Although the power stage of the developed laboratory system is a scaled down model and has limited ratings, the FBLC controller can be used equally effectively in a more realistic system set up. This is because the implementation of control algorithm includes appro-

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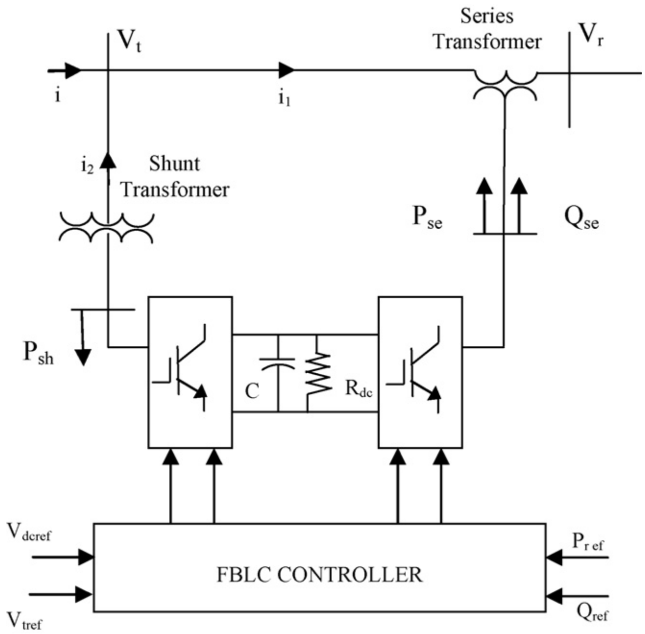

Fig. 1. Basic power system with UPFC.

priate scaling (down) factors for the fed-back signals of currents and voltages and also scaling (up) factors for initiating the inverter voltages. The feed-back linearization technique [10–12] is based on the idea of cancelling the non-linearities of the system and imposing a desired linear dynamics to control the system. The content of the paper is organized as follows. In Section 2 the modeling aspects of series converter, the shunt converter and the DC capacitor voltage are explained. In Section 3 basics of feed-back linearization control (FBLC) and its application are discussed. Simulation and experimental results of the proposed control scheme are presented in Section 5. Both power flow control and power oscillation damping issues are addressed.

2. System modeling

The per phase equivalent circuit of power system with UPFC is shown in Fig. 2.

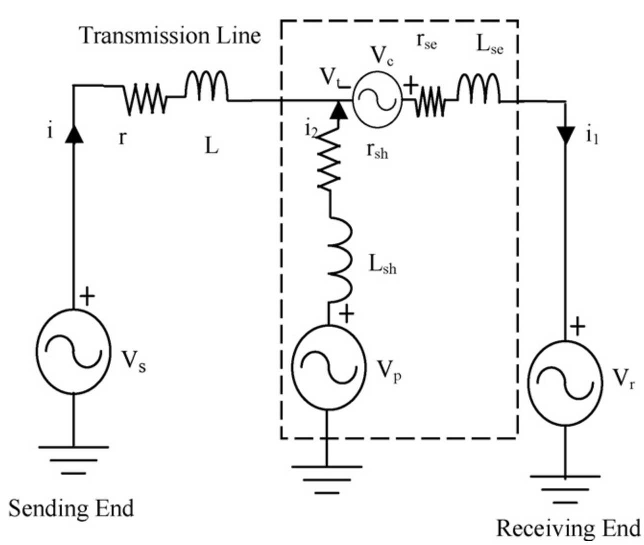

Fig. 2. Per-phase equivalent circuit of UPFC.

2.1. Modeling of series converter

To develop the series converter model, Kirchhoff's voltage equations (KVL) for the phase 'a' of the series branch (Fig. 2) can be written as

$$L_{se}\frac{di_{a1}}{dt} + i_{a1}r_{se} = (V_{ta} - V_{ra} + V_{ca}) \quad (1)$$

Similarly the KVL equations can be written for phases 'b' and 'c'. The KVL equations for three phases in matrix form can be written as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{bmatrix} = \begin{bmatrix} \frac{-r_{se}}{L_{se}} & 0 & 0 \\ 0 & \frac{-r_{se}}{L_{se}} & 0 \\ 0 & 0 & \frac{-r_{se}}{L_{se}} \end{bmatrix} \begin{bmatrix} i_{a1} \\ i_{b1} \\ i_{c1} \end{bmatrix} + \frac{1}{L_{se}} \begin{bmatrix} V_{ta} - V_{ra} + V_{ca} \\ V_{tb} - V_{rb} + V_{cb} \\ V_{tc} - V_{rc} + V_{cc} \end{bmatrix} \quad (2)$$

In Eq. (2) pertains to a–b–c reference frame. To ease the complexity, these equations are transformed from a–b–c reference frame to synchronous d–q reference frame selecting V_t as reference ($V_{td} = V_t$, $V_{tq} = 0$).

The differential equations for d–q components of series branch current can be written as

$$\frac{di_{d1}}{dt} = \frac{-r_{se}}{L_{se}}i_{d1} + \omega i_{q1} + \frac{1}{L_{se}}(V_{td} - V_{rd} + V_{cd}) \quad (3)$$

$$\frac{di_{q1}}{dt} = \frac{-r_{se}}{L_{se}}i_{q1} - \omega i_{d1} + \frac{1}{L_{se}}(V_{tq} - V_{rq} + V_{cq}) \quad (4)$$

2.2. Modeling of shunt converter

Proceeding in a similar way, the differential equations for the shunt converter current are given by

$$\frac{di_{d2}}{dt} = \frac{-r_{sh}}{L_{sh}}i_{d2} - \omega i_{q2} + \frac{1}{L_{sh}}(V_{pd} - V_{td}) \quad (5)$$

$$\frac{di_{q2}}{dt} = \frac{-r_{sh}}{L_{sh}}i_{q2} - \omega i_{d2} + \frac{1}{L_{sh}}(V_{pq} - V_{tq}) \quad (6)$$

2.3. Modeling of DC capacitor voltage

The performance of the UPFC depends on the stability of the dc link voltage between the series and shunt converters. In the case of ideal converters, the shunt converter must be capable of handling the amount of real power which is exchanged between the series converter and the line. Thus the UPFC as a whole exchanges zero real power with the transmission line. However, during dynamic conditions, the input power to the shunt converter should be equal to the sum of series injected power and the rate of change of stored energy in the capacitor on an instantaneous basis [2–4]. Thus, by power balance we obtain the equation below:

$$\frac{3}{2}\left[-V_{pd}i_{d2} - V_{pq}i_{q2}\right] = CV_{dc}\frac{dV_{dc}}{dt} + \frac{V_{dc}^2}{R_{dc}} + \frac{3}{2}[V_{cd}i_{d1} + V_{cq}i_{q1}]$$

and hence

$$\dot{V}_{dc} = \frac{3}{2CV_{dc}}[-V_{pd}i_{d2} - V_{pq}i_{q2} - V_{cd}i_{d1} - V_{cq}i_{q1}] - \frac{V_{dc}}{CR_{dc}} \quad (7)$$

The above equation governs the dc-link capacitor voltage of UPFC. The dc voltage level is controlled by regulating the real power flow from the ac system into the common dc-link via the shunt converter.