Power Control by UPFC with Three-Level Neutral Point Clamped Converter

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Abstract
A unified power-flow controller (UPFC) is the most versatile of these FACTS devices. A transmission line equipped with a UPFC can control the balance of the transmitted power between parallel lines and, as such, can optimize the use of the transmission grid for all parallel power flows. A UPFC is connected to the transmission line by coupling transformers, both with a shunt and with a series connection. The UPFC consists of two ac/dc converters, the ac sides connected to the shunt and series connection with the transmission line, and the dc sides connected back to back. A unified power-flow controller (UPFC) can enforce unnatural power flows in a transmission grid, to maximize the power flow while maintaining stability. Simulation and experimental results of a full three-phase model with no ideal transformers, series multilevel converter, and load neither confirm minimal control delay, and the presented controller can be used with any topology of voltage-source converters. In this paper, the direct power control is demonstrated in detail for a third-level neutral point clamped converter.

Index Terms—Direct power control, flexible ac transmission control (FACTS), multilevel converter, sliding mode control, unified power-flow controller (UPFC).

I. Introduction

Ac transmission lines form the backbone of the electricity grid in most countries and continents. The power flow will follow the path of least impedance and is uncontrollable, unless active grid elements are used. To enhance the functionality of the ac transmission grid, flexible ac transmission systems (FACTS) support the transmission grid with power electronics.

These devices offer a level of control to the transmission system operator [1], [2]. A unified power-flow controller (UPFC) is the most versatile of these FACTS devices. A transmission line equipped with a UPFC can control the balance of the transmitted power between parallel lines and, as such, can optimize the use of the transmission grid for all parallel power flows. A one-wire schematic of a transmission-line system equipped with a UPFC. A UPFC is connected to the transmission line by coupling transformers, both with a shunt and with a series connection. The UPFC consists of two ac/dc converters, the ac sides connected to the shunt and series connection with the transmission line, and the dc sides connected back to back. UPFCs are typically built with voltage-sourced converters, having a capacitor as (limited) dc energy storage.

An external control describes the set points of the power system (steady state or dynamic). The internal control describes the actual power electronics and safeties of the UPFC [3]. The external control is typically divided into a master and middle control [2]. The master control handles targets such as an optimal power system set point, increase of transient stability, or sub synchronous resonance damping and delivers the middle control set points. Middle control translates these master set points into set points for the series and shunt converter. The series and shunt controller can have [4], but do not require [5] and [6], internal communication for stability increase or optimization. The internal controller translates these middle-level control set points into switching decisions for the power-electronic components.

II. UPFC SERIES CONVERTER MODEL

During model construction and controller design, power sources $V_s$, $V_p$ are assumed to be infinite bus. We assume series transformer inductance and resistance negligible compared to transmission-line impedance. Connection transformers of series and shunt converters of the UPFC as in Fig. 1 are not explicitly included in the mathematical model used for controller design. Under these assumptions, we can simplify the grid as experienced by the UPFC to Fig. 1. Sending and receiving end power sources $V_s$, $V_p$ are connected by transmission line $L_r$. The total current drawn from the sending end $i_s$ consists of the current flowing through the line $i_s$ and the current exchanged with the shunt converter $i_p$. Shunt transformer inductance and resistance are represented by $L_p$ and $r_p$. The series inductance and resistance are commonly accepted as a model for overhead transmission lines of lengths up to 80 km. The power to be controlled is the sending end power, formed by the current $i_s$ and the sending end voltage $V_s$. This is the most realistic implementation for control purposes. The UPFC shunt converter model is similar and is not described in this paper; its functions and control are well described in literature [1], [2], [31] and the performance of the shunt converter is only of secondary influence on the
control system described in this paper, as demonstrated in previous work. Effects of dc bus dynamics are negligible in the control bandwidth of the power flow. For all simulations and experiments in this paper, the shunt converter is only used to satisfy active power flow requirements of the dc bus, differential equations that describe the current $i$ in three phases can be formulated. Voltages $V_{abc}=V_{a}^{c} + V_{b}^{c} + V_{c}^{c}$ are used for notation simplicity. The differential equations for the UPFC model are given as

$$L \frac{d}{dt} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} = -r \cdot \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} + \begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix} \quad (1)$$

Applying the Clarke and Park transformation results in differential equations in $d-q$ space. Voltages $V_{d}=V_{ad} + V_{cd}$ and $V_{q}=V_{aq} + V_{cq}$ are introduced for notation simplicity. It is assumed that the pulsation of the grid is known and varies without discontinuities. Applying the Laplace transformation and with substitution between the two $d-q$ space transfer functions, (2) is obtained, where currents $i_{sd}(S)$, $i_{sq}(S)$ are given in function of voltages $V_{d}(S)$ and $V_{q}(S)$

$$\begin{bmatrix} i_{sd}(s) \\ i_{sq}(s) \end{bmatrix} = \frac{1}{L} \cdot \begin{bmatrix} \left( \cos \frac{\omega}{2} + \sin \frac{\omega}{2} \right) \\ -\omega \cdot \left( \cos \frac{\omega}{2} + \sin \frac{\omega}{2} \right) \end{bmatrix} \cdot \begin{bmatrix} V_{d}(s) \\ V_{q}(s) \end{bmatrix} \quad (2)$$

Substituting (2) into (3), we receive the transfer functions, (2) is obtained, where currents $i_{sd}(s)$, $i_{sq}(s)$ are functions, linking active and reactive power requirements of the dc bus. The capacitor voltages $V_{c1}$ and $V_{c2}$ are influenced by the sum of the upper and lower leg currents $i_{g}$, and the input current $i_{0}$, as in

$$\begin{bmatrix} \frac{dU_{C1}}{dt} \\ \frac{dU_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} i_{C1} \\ i_{C2} \end{bmatrix} = \begin{bmatrix} \frac{i_{0} + i}{C_{1}} \\ \frac{i_{0} + i}{C_{2}} \end{bmatrix}$$

IV. DIRECT POWER CONTROL

Direct power control must ensure that the sending end power $P_{S}(t)$, $q_{S}(t)$ follows power references $P_{ref}$, $q_{ref}$. Defining the strong relative degree [6] of the controlled output $P_{S}(t)$, $q_{S}(t)$ as the minimum $\theta$-order time derivative, that contains a nonzero explicit function of the control vector $V_{c}$, and a sliding surface is a linear combination of the phase canonical state variable errors.

For $P_{S}(t)$ and $q_{S}(t)$, $i=1$ then

$$s_{i}(t) = K \cdot \left( \frac{p_{ref}(t) - P_{S}(t)}{P_{S}(t) - \Delta P_{S}(t)} \right) = 0$$

$$s_{i}(t) = K \cdot \left( \frac{q_{ref}(t) - q_{S}(t)}{q_{S}(t) - \Delta q_{S}(t)} \right) = 0$$

In (17), $K$ is a strictly positive constant; therefore, the only possibility for the system to uphold the surface equations $s_{i}(t) = 0$ is having the real power $P_{S}(t)$, $q_{S}(t)$ follow the references $P_{ref}(t)$, $q_{ref}(t)$. A control law that enforces the system to stay on these surfaces, or move toward them at all times, can be expressed as in (8), [4], [5].
V. MATLAB/SIMULINK RESULTS:
MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation.

Fig. 1. MATLAB Simulink model of the proposed circuit.
VI. CONCLUSION

The DPC technique was applied to a UPFC to control the power flow on a transmission line. The technique has been described in detail and applied to a three-level NPC converter. The main benefits of the control technique are fast dynamic control behavior with no cross coupling or overshoot, with a simple controller, independent of nodal voltage changes. The realization was demonstrated by simulation and experimental results on a scaled model of a transmission line. With shorter settling times, no overshoot, and indifference to voltage unbalance. We conclude that direct power control is an effective method that can be used with UPFC. It is readily adaptable to other converter types than the three-level converter demonstrated in this paper.

REFERENCES


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