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

Sathish Bakanagari, B. Karunakarrao, A. Maheshsh Kumar

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 dampening 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_R 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_R are connected by transmission line , . The total current drawn from the sending end i_T 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 $i_S$in three phases can be formulated. Voltages V_{abc}=$V_{s_{abc}}$ +$V_{C_{abc}}$ -$V_{R_{abc}}$ are used for notation simplicity. The differential equations for the UPFC model are given as

$$L\frac{d}{dt}\begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} = -r\cdot\begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} + \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Applying the Clarkeand Park transformation results in differential equations in *d-q* space. Voltages V_d=V_{sd} + V_{cd} -V_{Rd} and V_q=V_{sq} + V_{cq} -V_{Rq} 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 $V_q(S)$

$$\begin{bmatrix} i_{Sd}(s) \\ i_{Sq}(s) \end{bmatrix} = \frac{\frac{1}{L}\cdot\begin{bmatrix} \left(s+\frac{r}{L}\right) & \omega \\ -\omega & \left(s+\frac{r}{L}\right) \end{bmatrix}}{\left(\left(s+\frac{r}{L}\right)^2+\omega^2\right)}\cdot\begin{bmatrix} V_d(s) \\ V_q(s) \end{bmatrix}$$

Substituting (2) into (3), we receive the transfer functions, linking $P_S(S)$, $Q_S(S)$, toV_S , V_R, and . Both active and reactive power consist of an uncontrollable constant part, which is determined by power source voltages , and line impedance , and a controllable dynamic part, determined by converter voltage $V_C(S)$, as made explicit in

$$P_S(s) = P_{S0}(V_S, V_R) + \Delta P_S(V_C(s))$$
$$Q_S(s) = Q_{S0}(V_S, V_R) + \Delta Q_S(V_C(s)).$$

Splitting in a constant uncontrollable and a dynamic controllable part results in (5) and (6). For notation simplicity, $V_{Cd}(S)$, $V_{Cq}(S)$, are replaced by V_{Cd}, V_{Cq}

$$P_{S0}(V_S, V_R) = V_{Sd}\cdot\frac{((V_{Sd}-V_{Rd})\cdot r - \omega\cdot L\cdot V_{Rq})}{r^2+(\omega\cdot L)^2}$$
$$Q_{S0}(V_S, V_R) = V_{Sd}\cdot\frac{(V_{Rq}\cdot r + \omega\cdot L\cdot(V_{Sd}-V_{Rd}))}{r^2+(\omega\cdot L)^2}$$

III. THREE-LEVEL NEUTRAL POINT CLAMPED CONVERTER

A schematic of a three-level neutral point clamped converter,This topology and its mathematical model have been diligently described in [5]. Each leg of the converter consists of four switching componentsS_{k1}, S_{k2}, S_{k3}, S_{k4}, and two diodes $D_{k1}$and D_{k2}. The diodes D_{k1}, D_{k2}, clamp the voltages of the connections between S_{k1}, S_{k2}, and S_{k3}, S_{k4} , , respectively, to the neutral point, between capacitors C_1, C_2. There are three possible switching combinations for each leg k , thus three voltages u_{mk}. The three levels for voltages u_{mk} produce five different converter phase-output voltages u_k. The upper and lower leg currents I_k, I_k'or their respective sum*i, i'* can be described in function of the output line currents . The system state variables are the line currents $i_1, i_2, i_3$and the capacitor voltages U_{c1}, U_{c2}. This system has the dc-bus current $i_0$and the equivalent load source voltages U_{ek}as inputs. Under the assumption that the converter output voltages $U_k$are connected to an r_{eq}, L_{eq}system with a sinusoidal voltage source $u_k$with isolated neutral, we can write the equations for the three-phase currentsi_1, i_2, i_3 as in

$$L_{\text{eq}}\cdot\frac{di_k}{dt} = U_k - r_{\text{eq}}\cdot i_k - U_{\text{eqk}}$$

The capacitor voltagesU_{c1}, U_{c2} are influenced by the sum of the upper and lower leg currents i_0, and the input current i_0', as in

$$\frac{dU_{C_1}}{dt} = \frac{i_{C_1}}{C_1} = \frac{i_0 + i}{C_1}$$
$$\frac{dU_{C_2}}{dt} = \frac{i_{C_2}}{C_2} = \frac{i_0' + i'}{C_2}$$

IV. DIRECT POWER CONTROL

Direct power control must ensure that the sending end power $P_S(t)$, $q_S(t)$follows power references P_{Sref} , q_{Sref}. Defining the strong relative degree [6] of the controlled output $P_S(t)$, $q_S(t)$ as the minimum th-order time $d^i(p_S(t))/dt^i,\ d^i(q_S(t))/dt^i$ derivative, that contains a nonzero explicit function of the control vector V_C, a suitable sliding surface is a linear combination of the phase canonical state variable errors.

For $P_S(t)$and $q_S(t)$, *i*=1 then

$$s_d(t) = K\cdot(p_{Sref}(t) - p_S(t)) = K\cdot(\Delta p_{Sref}(t) - \Delta p_S(t)) = 0$$

$$s_q(t) = K\cdot(q_{Sref}(t) - q_S(t)) = K\cdot(\Delta q_{Sref}(t) - \Delta q_S(t)) = 0$$

In (17), K is a strictly positive constant; therefore, the only possibility for the system to uphold the surface equations $S_d(t)$, $S_q(t)$=0 is having the real power $P_S(t)$, $q_S(t)$ follow the references $P_{Sref}(t)$, $q_{Sref}(t)$. 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.

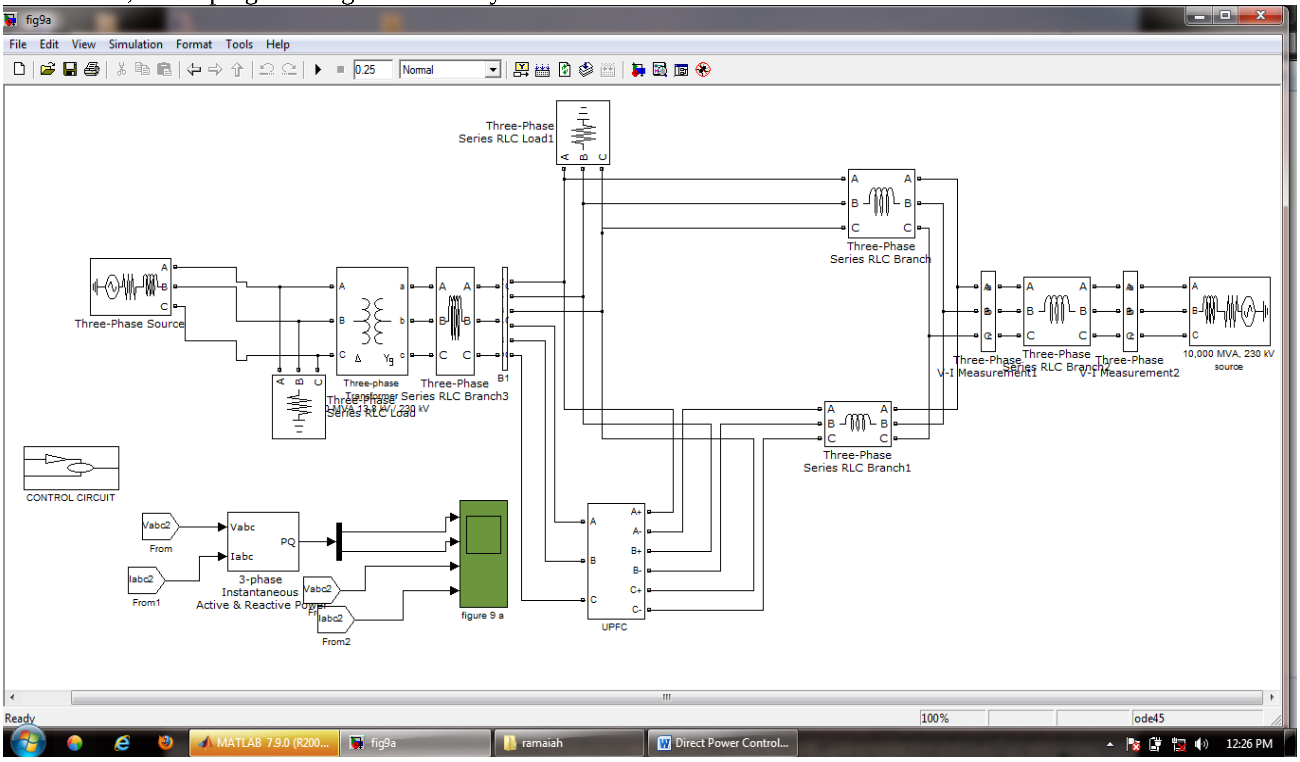
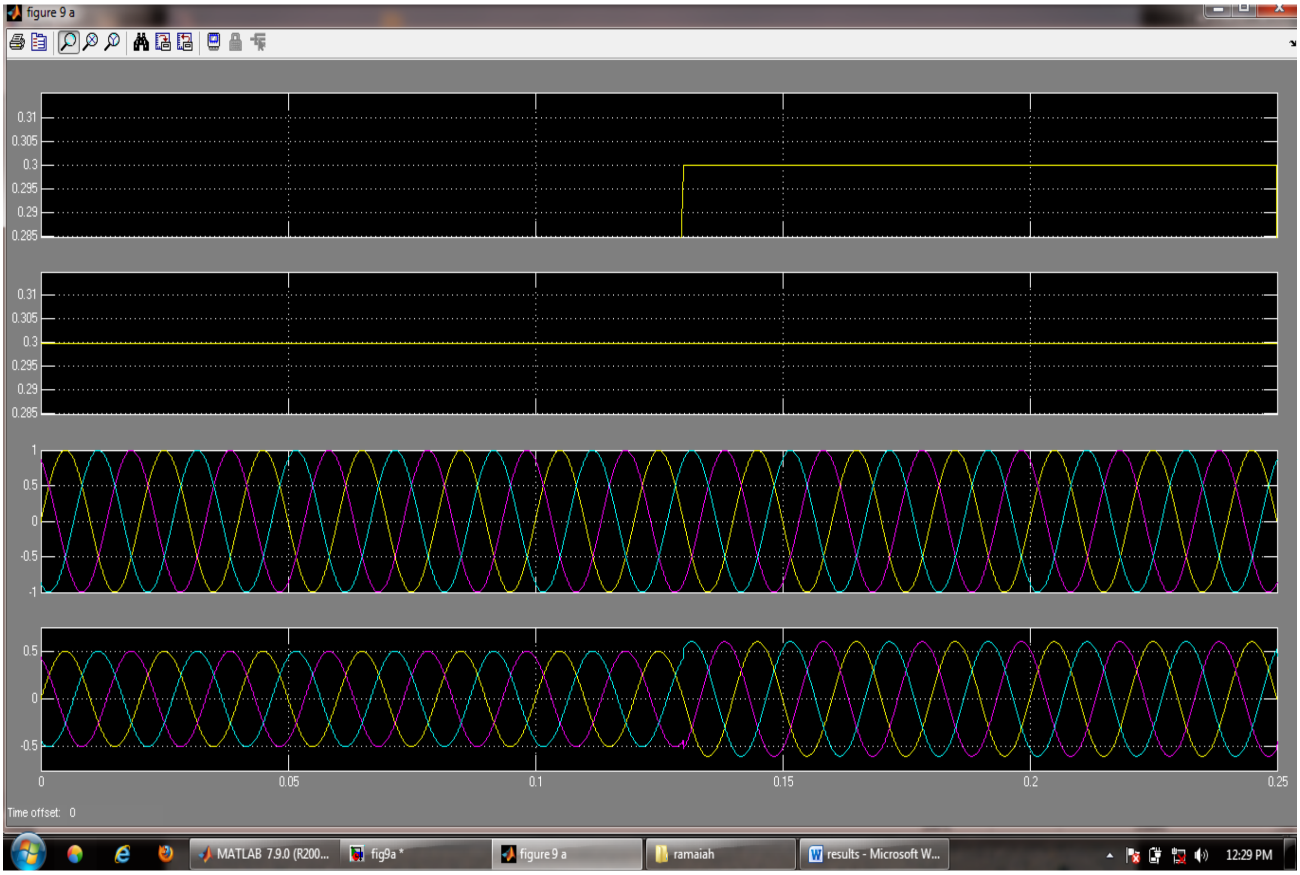


Fig.1.matlab Simulink model of the proposed circuit.



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.

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