Abstract-A unified power-flow controller (UPFC) maintain stable operation can enforce unnatural powerflows in a transmission grid, to maximize the power flow while maintaining stability. Theoretically, active and reactive power flow can be controlled without overshoot or cross coupling. This paper develops direct power control, based on instantaneous power theory, to apply the full potential of the power converter by upfc and controlling through fuzzy. Simulation and experimental results of a full three-phase model with non-ideal transformers, series multilevel converter, and load confirm minimal control delay, no overshoot nor cross coupling. A comparison with other controllers demonstrates better response under balanced and unbalanced conditions. Direct power control is a valuable control technique for a UPFC, 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. Here the improvement of power is done through fuzzy logic controller.

I. INTRODUCTION

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]. 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. 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 unified power-flow controller (UPFC) is the most versatile of these FACTS devices. A one-wire schematic of a transmission-line system equipped with a UPFC is given in Fig. 1.

A UPFC is connected to the transmission line by using 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.

Fig. 1. One-wire schematic of the transmission line with UPFC.

UPFCs are typically built with voltage-sourced converters, having a capacitor as (limited) dc lin or dc energy storage. In Fig. 2, an overview of the most common control structure for UPFCs is displayed. An external control describes the setpoints 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 setpoint, increase of transient stability, or sub synchronous resonance dampening and delivers the middle control setpoints. Middle control translates these master setpoints into setpoints.
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 setpoints into switching decisions for the power-electronic components. Higher level control techniques have primarily focused on optimizing power flow [1]. Later on, the focus shifted to damping subsynchronous resonances of turbine generator shafts and interarea oscillations [7]–[11] and transient stability increase [12]. Various methods are used to switch intelligently between higher level control priorities [7], [13]. Recently, a lot of interest into the increase of grid reliability is shown [14]. The first designs of middle-level power-flow controllers for UPFC used direct control which suffered from serious cross coupling [15]. Decoupling control improved this cross-coupling, with high sensitivity to system parameter knowledge [16], and cross-coupling control of direct and quadrature series-injected voltages to active and reactive power improved on that. Cross-coupling control with direct control oscillation damping [8] enhanced performance, but based on PI control structures, realized a low control bandwidth [16], [17]. The instantaneous power concept [18]–[20] enabled faster control techniques, putting, however, a larger strain on the computational capacity of the controllers [5], [21]. The controller proposed in this paper combines two control levels—the middle-level series converter control and internal converter control—thereby increasing the simplicity of the controller and increasing the control dynamics. Since the series converter is typically used for power-flow control, the controller realizes a direct relation between the desired power flow and switching states, and is therefore named a direct power controller (DPC). In Fig. 2, the precise location of the proposed DPC is displayed. The direct power control technique used in this paper finds its design principles in instantaneous power theory [22], [23] and sliding mode control [24]–[26]. Relying on these two techniques, a sliding surface is defined in function of the instantaneous active and reactive power, and the system is controlled to stay on the surface. A similar controller was developed for a matrix converter [27]. This paper is a follow up paper to [28], with a more detailed explanation of the controller design and a comparison to other controllers. The series and shunt converter of a UPFC are HV power electronics. To minimize the voltage stress on all components while increasing the system voltage level, multilevel neutral point clamped inverters are a promising topology. The DPC control method described in this paper is divided in two parts—a general external part and an internal topology-specific part. The design principles for both are explained in detail. The external part is universal, the internal part can easily be adapted to different topologies of voltage-source converters. In this paper, a three-level neutral point clamped converter is used. Other
converter topologies use the converter independent part without further theoretical development. The converter topology dependent part can be deduced analogously to the given example. The model of the UPFC will be developed in Section II. All assumptions made will be mentioned and clarified. In Section III, the three-level inverter’s topology, its mathematical model, and the derived system equations will be explained in full. In Section IV, the direct power control will be constructed and its theoretical functionality demonstrated. The topology-dependent part is developed for a three-level NPC converter based on Section III. Simulation and experimental results are demonstrated in Section V. The experimental setup is discussed in detail. Conclusions regarding the DPC method, its application for UPFC, and the interaction on the control of a multilevel converter are given in Section VI.

FUZZY LOGIC CONTROLLER:

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as: i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani’s „min” operator. v. Defuzzification using the „height” method.

\[ E(k) = \frac{P_{ph(k)} - P_{ph(k - 1)}}{V_{ph(k)} - V_{ph(k - 1)}} \]

\[ CE(k) = E(k) - E(k - 1) \]

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular \( E(k) \) input there is only one dominant fuzzy subset. The input error for the FLC is given as

MEMBERSHIP FUNCTIONS

Fuzzification:

Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM 5 (Positive Medium), and PB (Positive Big). The
II. UPFC SERIES CONVERTER MODEL

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. During model construction and controller design, power sources $V_s, V_r$, are assumed to be in finite bus. We assume series transformer inductance and resistance negligible compared to transmission-line impedance. Under these assumptions, we can simplify the grid as experienced by the UPFC to Fig. 3. Sending and receiving end power sources $V_s, V_r$, are connected by transmission line $rL$.

The total current taken from the sending end $i_p$ consists of the current flowing through the line and the current interchanged with the shunt converter $i_s$. Shunt transformer inductance and resistance are represented by $L_p, r_p$ and $L_s, r_s$. The series inductance and resistance are basically taken as a model for overhead transmission lines of lengths up to 80 km [29],[30]. The power to be controlled is the sending end voltage $V_s$. This is the ongoing implementation for control purposes. Effects of dc bus dynamics are forgettable 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. Using the model of Fig. 3, differential equations that describe the current in three phases can be formulated. Voltages are used for notation simplicity. The differential equations for the UPFC model are given as

$$\frac{L}{d^2} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = -r \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

(1)

Applying the Clarke and Park transformation results in differential equations in space. Voltages $V_a = V_{sd} + V_{ca} - V_{rd}$ 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 space transfer functions, (2) is obtained, where currents $i_{sd}(s)$, $i_{sq}(s)$ are given in function of voltages $V_a(s)$ and $V_q(s)$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \frac{1}{L} \begin{bmatrix} \omega \\ -\omega \end{bmatrix} + \begin{bmatrix} \frac{V_a(s)}{L} \\ \frac{V_q(s)}{L} \end{bmatrix}$$

(2)

The active and reactive power of the power line are determined only by the current over the line and the sending end voltage. Without losing generality of the solution, we synchronize the DQ transformation on $V_{sa}$, resulting in $\Delta \phi$. Assuming relative voltage stability, $V_{sd}(s) = V_{da}, VR_{dq}(s) = VR_{dq}$ Active and reactive power at the sending end are calculated as

$$P_S(t) = V_{sd}i_{sd}(t)$$
$$P_S(s) = V_{sd}i_{sd}(s)$$

$$Q_S(t) = -V_{sq}i_{sq}(t)$$
$$Q_S(s) = -V_{sq}i_{sq}(s)$$

(3)

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

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

(4)

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

$$P_{sd}(V_S, V_R) = V_{sd} \frac{(V_{sd} - V_{rd})r - \omega L V_{rq}}{r^2 + (\omega L)^2}$$

$$Q_{sd}(V_S, V_R) = V_{rd} \frac{V_{rq}r + \omega L (V_{sd} - V_{rd})}{r^2 + (\omega L)^2}$$

(5)
It is clear that only \( V_{cd}(t) \) effects the derivative \( \frac{d\Delta p_k(t)}{dt} \) instantaneously, and only \( V_{cq}(t) \) effects the derivative \( \frac{d\Delta q_k(t)}{dt} \) instantaneously.

### III. THREE-LEVEL NEUTRAL POINT CLAMPED CONVERTER

This topology and its mathematical model have been described in [32]. A schematic of a three-level neutral point clamped converter is given in Fig. 4. Each leg \( k \) of the converter consists of four switching components \( S_{k1}, S_{k2}, S_{k3} \) and \( S_{k4} \) 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 \( C_1 \) and \( C_{25} \). There are three possible switching combinations for each leg \( k \) thus three voltages \( u_{mk} \). The three levels for voltages 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 \( i_k \) and the capacitor voltages \( [32] \). This system has the dc-bus current and the equivalent load source voltages as inputs. Under the assumption that the converter output voltages are connected to an , system with a sinusoidal voltage source with isolated neutral, as in Fig. 4, we can write the equations for the three-phase currents \( i_1, i_2, i_3 \) as in

\[
L_{eq} \frac{di_k}{dt} = U_k - r_{eq}.i_k - U_{eqk}
\]

The capacitor voltages, \( U_{c1}, U_{c2} \) are influenced by the sum of the upper and lower leg currents \( i, i' \), and the input current \( i_0, i'_0 \) as in

\[
\frac{du_{c1}}{dt} = \frac{i_{c1}}{c_1} - \frac{i_{c0}}{c_1}
\]

\[
\frac{du_{c2}}{dt} = \frac{i_{c2}}{c_2} - \frac{i_{c0}}{c_2}
\]

From the restrictions on the states of the switching devices in each leg of the converter, we can define the ternary variable \( y_k(t) \), representing the switching state of the entire leg, as

\[
y_k(t) = \begin{cases}
(S_{k1}, S_{k2} = on)A (S_{k3}, S_{k4} = off) \rightarrow 1 \\
(S_{k2}, S_{k3} = on)A (S_{k1}, S_{k4} = off) \rightarrow 0 \\
(S_{k3}, S_{k4} = on)A (S_{k1}, S_{k2} = off) \rightarrow -1
\end{cases}
\]
To simplify notation, combinations of this variable, \( \gamma_k \), \( T \), and \( \epsilon \), are introduced

\[
\Gamma_{1k} = \frac{\gamma_k}{2} (1 + \gamma_k) \\
\Gamma_{2k} = \frac{\gamma_k}{2} (1 - \gamma_k)
\]

To describe the dimension. The levels and vector \( \epsilon = \lambda T \) of the capacitors, \( \epsilon = \epsilon \) are aiding for the sign, are equal. To know \( \epsilon \), \( \lambda \). (a) Five levels in \( \alpha, \beta \). (b) Five levels in \( \beta, \lambda \).

**TABLE I**

<table>
<thead>
<tr>
<th>Vector</th>
<th>( \gamma_1 )</th>
<th>( \gamma_2 )</th>
<th>( \gamma_3 )</th>
<th>( C \cdot d \left( U_{C1} - U_{C2} \right) / dt )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>( -i_3 - i_2 )</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>( -i_2 )</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( -i_1 )</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>( -i_2 )</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>( -2 \cdot i_2 )</td>
</tr>
<tr>
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<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>( i_1 )</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>( -i_2 )</td>
</tr>
<tr>
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<td>0</td>
<td>-1</td>
<td>1</td>
<td>( -i_3 - 2 \cdot i_2 )</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( i_3 + i_2 )</td>
</tr>
<tr>
<td>14</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>( i_3 + i_2 )</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>( i_2 + 2 \cdot i_3 )</td>
</tr>
<tr>
<td>17</td>
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<td>1</td>
<td>0</td>
<td>( -i_2 )</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>( -i_3 )</td>
</tr>
<tr>
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<td>-1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>( -i_3 - i_2 )</td>
</tr>
<tr>
<td>21</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>( 2 \cdot i_3 )</td>
</tr>
<tr>
<td>22</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>( i_2 )</td>
</tr>
<tr>
<td>23</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>( -i_3 )</td>
</tr>
<tr>
<td>24</td>
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<td>0</td>
<td>0</td>
<td>( -2 \cdot i_3 )</td>
</tr>
<tr>
<td>25</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>( 2 \cdot i_3 )</td>
</tr>
<tr>
<td>26</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
</tbody>
</table>

If we assume the voltage balance of the capacitors, \( C_1, C_2 \), the 27 possible combinations of leg switching state variables, \( \gamma_1, \gamma_2, \gamma_3 \), lead to 27 sets of phase voltages, \( U_1, U_2, U_3 \), 27 voltage vectors after Clark transformation to \( \alpha, \beta \)-space. The 27 voltage vectors can be divided in 24 active vectors and 3 null vectors. The 24 active vectors form 18 unique vectors; 12 vectors form 6 redundant pairs. The 3 null vectors also form only 1 unique vector. This results in 19 different voltage vectors. To simplify the vector selection, the 27 vectors are grouped into 5 levels in the \( \gamma_1, \gamma_2, \gamma_3 \) dimension, based on their component in this dimension. The levels and vector grouping are represented in Fig. 5. Each combination of levels, \( \gamma_1, \gamma_2 \), corresponds to one unique voltage vector. Assuming that the capacitors, \( C_1, C_2 \), have equal capacity and using the relation of the three line currents \( i_1 + i_2 + i_3 = 0 \), the dynamics of the voltage balance \( U_{C1}, U_{C2} \) can be derived from (14), leading to

\[
\frac{d}{dt} (U_{C1} - U_{C2}) = \frac{v_1^2 - v_2^2}{c} i_1 + \frac{v_2^2 - v_3^2}{c} i_2
\]
the sign of the instantaneous active power $P$ will be used. Since $U_{DC}$ will always be positive, the sign of depends only on the sign of $\gamma_{123}$. Assuming perfect voltage balance $U_{C1} - U_{C2}$ the instantaneous outgoing power of the converter is given by the internal product of the switching state variables $\gamma_{123}$ and outgoing line currents scaled by the capacitor voltage by

$$P = \gamma_{123} \cdot i_{123} \cdot \frac{U_{DC}}{2}$$

(16)

IV. DIRECT POWER CONTROL

Direct power control must ensure that the sending end power, follows power references $P_{ref}(t)$, $q_{ref}(t)$, $i_{ref}(t)$. Defining the strong relative degree [26] of the controlled output, $P_{s}(t),q_{s}(t)$ as the minimum th-order time derivative $d^l(P_{s}(t))/dt^l$ of $(q_{s}(t))/dt^l$, that contains a nonzero explicit function of the control vector, a suitable sliding surface is a linear combination of the phase canonical state variable errors. For $P_{s}(t),q_{s}(t)$ and $i_{s}=1$, then

$$s_d(t) = K_s(p_{s}(t) - p_{s}(t)) = K_s(\Delta p_{s}(t) - \Delta p_{s}(t)) = 0$$

$$s_q(t) = K_s(q_{s}(t) - q_{s}(t)) = K_s(\Delta q_{s}(t) - \Delta q_{s}(t)) = 0$$

(17)

In (17), 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 $p_d(t),q_d(t)$, following the references $p_{s}(t),q_{s}(t)$, . A control law that enforces the system to stay on these surfaces, or move toward them at all times, can be expressed in

$$s_d(t) \cdot s_d(t) < 0$$

$$s_q(t) \cdot s_q(t) < 0$$

(18)

where $s_d(s),s_q(s)$ are governed by system dynamics involved (6). To uphold (18), the inverter has to appropriately change the sign of the derivatives $s_d(t),s_q(t)$. Using the results of the initial value theorem on the derivative of the sending end power in (7), the following equation can be developed

$$\lim_{t \to 0^-} \frac{ds_d(t)}{dt} = \lim_{s \to \infty} s \cdot s \cdot s_{d}(s)$$

$$\lim_{t \to 0^+} \frac{ds_q(t)}{dt} = \lim_{s \to \infty} s \cdot s \cdot s_{q}(s)$$

(19)

From (19), it can be concluded that to instantaneously in fluence $s_d(t),V_{sd}(t)$, should be used. Similarly, for $S_q(t)$, it is done best by $V_{sq}(t)$. It is also clear from (19) that impulse or step changes in $\Delta p_s(t),\Delta q_{sref}(t)$, cannot be followed instantaneously, yet ramps in $\Delta p_s(t),\Delta q_{sref}(t)$, can be followed, providing their rate of change is less than $\left(\max \frac{V_{ca}}{L}, V_{sd} \left(\max \frac{V_{ca}}{L} \right), V_{sd}\right)$ and the combination cannot exceed

$$\frac{d\Delta p_{sref}(t)^2}{dt} + \frac{d\Delta q_{sref}(t)^2}{dt} < \frac{V_{C_{max}}^2}{L^2} \cdot V_{sd}^2$$

(20)

Considering this conclusion, it is important to determine the conditions to reach the direct power control surfaces using the final value theorem

$$\lim_{t \to \infty} s_{d}(t) = \lim_{s \to \infty} s \cdot s \cdot s_{d}(s)$$

$$\lim_{t \to \infty} s_{q}(t) = \lim_{s \to \infty} s \cdot s \cdot s_{q}(s)$$

(21)

From (21), several important conclusions can be drawn. The control can only handle limited steps or ramps of decaying derivative in references $\Delta p_{sref},\Delta q_{sref}$, . Also, a clear limit exists to the controllable reference steps, limited by the maximum UPFC series output voltage amplitude $U_{max}$ as

$$\Delta p_{sref}(t)^2 + \Delta q_{sref}(t)^2 < \frac{V_{C_{max}}^2}{r^2 + \omega^2 L^2}$$

(22)

In the selection Power to desired change in of Fig. 6, the implementation of 19 exists. To select a physical voltage vector, this decision process is transformed to the domain, remaining with requested changes of the UPFC series output voltage in $\alpha \beta$ to the output voltage vector. To limit the switching frequency, the decision is suppressed until the system state crosses a
parallel surface at a certain distance from the direct power control surfaces $\Delta S$. Note that this requested change is not expressed in a numeric value of the requested change, but as the direction of change (in this case, a ternary variable, indicating increase, no change, decrease).

Depending on the currently used output vector and the requested change in $\gamma$, an appropriate next vector can be selected. This concludes the converter topology independent part of the controller. In Fig. 6, in the selection Desired change in $\gamma$ to output Voltage, for a three-level NPC converter, the voltage vector selection is displayed. DPC demands increasing or decreasing the output voltage vector in the and direction. Based on the currently applied vector and this demand, the next vector is selected. This is simplified to selection of the voltage vector levels. In the cases that vectors coincide, an extra criterium is needed to unambiguously select a set of switching.

\[
\begin{array}{cccccc}
\lambda_{\alpha} & \lambda_{\beta} & -2 & -1 & 0 & 1 & 2 \\
2 & 21 & 21 & 16 & 3 & 3 \\
1 & 20 & 22 & 15.22 & 15 & 4 \\
0 & 19 & 23 & 1,14,27 & 10 & 9 \\
-1 & 24 & 26 & 11,26 & 11 & 8 \\
-2 & 25 & 25 & 12 & 7 & 7
\end{array}
\]

state variables $\gamma_1, \gamma_2, \gamma_3$. Even though the voltage vectors may realize the same phase voltages $U_1, U_2, U_2$ the precise switching state $\gamma_1, \gamma_2, \gamma_3$, also determines whether energy is

\[
(U_{c1} - U_{c2}) \cdot \frac{d(U_{c1} - U_{c2})}{dt} < 0 \quad (23)
\]

To maintain voltage balance, $U_{c1} - U_{c2} = 0$ (23) must be upheld at all times. This is displayed in Fig. 6 in selection Capacitor voltage balance control. Depending on the sign of the voltage unbalance $U_{c1} - U_{c2}$ and output power, the voltage vector can be selected so that (23) is upheld. Vector selection, in function of demand for change of the voltage vector in $\gamma$, dimension and capacitor voltage unbalance is given in Table II(a) and (b). To limit the output frequency, the size of the voltage unbalance $U_{c1} - U_{c2}$ has to reach a certain level $\Delta U_C$ before it is addressed. In this application, it is enforced by a relay system. The last degree of freedom is within the selection of the null vector 1, 14, 27. They have the same effect on the output voltage and capacitor voltage imbalance $U_{c1} - U_{c2}$. To minimize the switching losses, the null vector could be chosen within least switching distance from the previous vector. As such, any order from a higher controller to change the output voltage $U$ in $a\beta$ is translated unambiguously into a voltage-output vector. This voltage vector selection method is well covered, including the necessary balancing of the capacitor voltages by [32].
V. RESULTS

Fig. 7. Laboratory setup.

Fig. 8. UPFC series converter controlling power flow under balanced conditions, 2.5-s view during stepwise changes of active and reactive power flow reference $P_{\text{ref}}, Q_{\text{ref}}$. (a) Simulation (P 948 Wpu, Q948 VArpu) ($U_a, U_b, U_c$ 230 Vpu) ($i_a, i_b, i_c$ 2.38 Apu). (b) Experimental, (CH1: P40 W/V, CH2: Q40 VAr/V, 5 V/div) (CH3, CH4: $i_a, i_b$ 0.22 A/V, 5 V/div). (c) Simulation (P 948 Wpu, Q948 VArpu) ($U_a, U_b, U_c$ 230 Vpu) ($i_a, i_b, i_c$ 2.38 Apu). (d) Experimental, (CH1: P40 W/V, CH2: Q40 VAr/V, 5 V/div) (CH3, CH4: $i_a, i_b$ 0.22 A/V, 5 V/div).

Fig. 9. UPFC series converter controlling the power flow under balanced conditions, 250-ms view during stepwise change of active and reactive power flow reference $P_{\text{ref}}, Q_{\text{ref}}$. (a) Simulation (P 948 Wpu, Q948 VArpu) ($U_a, U_b, U_c$ 230 Vpu) ($i_a, i_b, i_c$ 2.38 Apu). (b) Experimental, (CH1: P40 W/V, CH2: Q40 VAr/V, 5 V/div) (CH3, CH4: $i_a, i_b$ 0.22 A/V, 5 V/div). (c) Simulation (P 948 Wpu, Q948 VArpu) ($U_a, U_b, U_c$ 230 Vpu) ($i_a, i_b, i_c$ 2.38 Apu). (d) Experimental, (CH1: P40 W/V, CH2: Q40 VAr/V, 5 V/div) (CH3, CH4: $i_a, i_b$ 0.22 A/V, 5 V/div).

Table II

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Fig. 8(a)–(d) demonstrates that the system can handle any combination of sending end power references $P_{ref}, Q_{ref}$ and reference changes $\Delta P_{ref}, \Delta Q_{ref}$.

Fig. 10. UPFC series converter controlling power flow, comparison between controllers DPC (-) ADC(-) [5] DIC (-) [21]. (a) Simulation under balanced conditions, simultaneous step in active and reactive power references $P_{ref}, Q_{ref}$ 250-ms view (P948 Wpu, Q948 VArpu). (b) Simulation under balanced conditions, simultaneous step in active and reactive power references $P_{ref}, Q_{ref}$ 6 ms view (P 948 Wpu, Q948 VArpu). (c) Simulation under unbalanced conditions, 70% single-phase voltage sag at 0.125 s, 250-ms overview (P 948 Wpu, Q948 VArpu) ($U_{Sa}, U_{Sb}, U_{Sc}$ 230 Vpu).

### VI. CONCLUSION

To UPFC the DPC technique was applied to control the power flow on a transmission line and maintaining stable power. And fuzzy also used for controlling. 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. The controller was compared to few other controllers under balanced and unbalanced conditions, and demonstrated good performance, with less settling times, no overshoot, and in difference to voltage unbalance. We finally found that direct power control is an effective method that can be used with UPFC for controlling the power. And fuzzy also used as a effective controller than compared to other controllers. It is readily adaptable to other converter types than the three-level converter demonstrated in this paper.

### REFERENCES