Abstract - In the recent years, due to economics and environment problems, build of new power planet and transmission line become more difficult. Hence it is advisable to enhance power transfer capability of the existing transmission lines up to thermal limit instead of constructing new one. For enhancing the power capability, FACTS controller like SSC, TCSC, SVC are developed. But these controllers cannot compensate the real and reactive power separately. For this a controller called, Unified Power Flow Controller (UPFC) is developed which uses both the series and shunt controller with a common DC capacitor link. This capacitor brings several disadvantages such as affecting the reliability, high cost etc. This paper proposes a new topology for UPFC based on the Matrix converter design. Matrix converters (MCs) allow the direct ac/ac power conversion without dc energy storage links; therefore, the MC-based UPFC (MC-UPFC) has reduced volume and cost, reduced capacitor power losses, together with higher reliability. Theoretical principles of direct power control (DPC) based on sliding mode control techniques are established for an MC-UPFC dynamic model including the input filter. As a result, line active and reactive power, together with ac supply reactive power, can be directly controlled by selecting an appropriate matrix converter switching state guaranteeing good steady-state and dynamic responses.

I. INTRODUCTION

The original UPFC concept, introduced in the nineties by L.Gyugyi [1], consists of two AC-DC converters using Gate-Turn Off thyristors (GTO), back to back connected through their common DC link using large high-voltage DC storage capacitors. This arrangement can be operated as an ideal reversible AC-AC switching power converter, in which the power can flow in either direction between the AC terminals of the two converters The DC link capacitors provide some energy storage capability to the back to back converters that help the power flow control. Replacing the two three-phase inverters by one matrix converter the DC link (bulk) capacitors are eliminated, reducing costs, size, maintenance, increasing reliability and lifetime. The AC-AC matrix converter, also known as all siliconconverter, processes the energy directly without large energy storage needs. This leads to an increase of the matrix. In [3] an UPFC-connected power transmission network model was proposed with matrix converters and in [3] was used to synthesize both active (P) and reactive (Q) power controllers using a modified Venturini high-frequency PWM modulator. In this paper a Matrix Converter based UPFC-connected power transmission network model is proposed, using a Direct Power Control approach (DPC-MC). This control method is based on sliding mode control techniques [5] and allows real time selection of adequate state-space vectors to control input and output variables.

II. MODELING OF UPFC POWER SYSTEM

A. General architecture

A simplified power transmission network of DPC technique applied to the three phase Matrix Converter (MC) operated as UPFC is presented in Fig. 1, where VS and VR are the sending-end and receiving-end sinusoidal voltages of the GS and GR generators respectively. The MC is connected to the inductive transmission line, represented by inductance and series resistance (L2 and R2), through coupling transformers T1 and T2.
Fig. 2 shows the simplified three-phase equivalent circuit of the matrix UPFC transmission system model. For system modeling, the power sources and the coupling transformers are all considered ideal.

\[ \frac{dI_q}{dt} = -\omega I_q - \frac{R_2}{L_2} I_q + \frac{1}{L_2} (V_{Lq} - V_{Roq}) \]  

(2)

The active and reactive power of sending end generator [19] are given in coordinates by

\[ \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \]  

(3)

Assuming \( V_{Roq} \) and \( V_{sd} \) as constants and a rotating reference frame synchronized to the \( V_s \) source so that \( V_{sq} = 0 \), active and reactive power \( P \) and \( Q \) are given by (4) and (5), respectively.

\[ P = v_d i_d \]  

(4)

\[ Q = -v_q i_q \]  

(5)

B. Matrix Converter Output Voltage and Input Current Vector

A diagram of the UPFC system (Fig. 3) includes the three-phase shunt input transformer (with windings \( Ta, Tb, Tc \)), the three-phase series output transformer (with windings \( TA, TB, TC \)) and the three-phase matrix converter, represented as an array of nine bidirectional switches \( Skj \) with turn-on and turn-off capability, allowing the connection of each one of three output phases directly to any one of the three input phases.

\[ \frac{di_d}{dt} = \omega i_q - \frac{1}{2l} v_d - \frac{1}{2\sqrt{2}l} v_q + \frac{1}{l} v_{ld} \]

Fig. 4. (a) Input voltages and their corresponding sector
(b) Output voltage state-space vectors when the input voltages are located at sector

Applying coordinates to the input filter state variables presented in Fig. 3 and neglecting the effects of the damping resistors, the following equations are obtained.
The errors Ep and Eq – ref \( \omega \) – since from the control viewpoint, its \( \rho < P \) < ref it - t - P 0 < Q < ref ?, therefore, transmission P P t 0 < Q < ref - p - > P i, then, the robust sliding surfaces must be proportional to these errors, being zero after reaching sliding mode. 
\[ S_p(e_p, t) = K_p(P_{ref} - P) = 0 \]
\[ S_q(e_Q, t) = K_q(Q_{ref} - Q) = 0 \]
The proportional gains kp and kq are chosen to impose appropriate switching frequencies.

B. Line Active and Reactive Power Direct Switching Laws

The DPC uses a nonlinear law, based on the errors Ep and Eq to select in real time the matrix converter switching states (vectors). Since there are no modulators and/or pole zero-based approaches, high control speed is possible. To guarantee stability for active power and reactive power controllers, the sliding-mode stability conditions (12) and (13) must be verified
\[ S_p(e_p, t) \dot{S}(e_p, t) < 0 \quad (12) \]
\[ S_q(e_Q, t) \dot{S}(e_Q, t) < 0 \quad (13) \]

According to (10) and (12), the criteria to choose the matrix Vector should be
\[ S_p(e_p, t) > 0 \Rightarrow \dot{S}(e_p, t) < 0 \Rightarrow \dot{S}(e_p, t) < 0 \]
\[ \Rightarrow P < P_{ref} \]

Then choose a vector suitable to increase P
\[ S_p(e_p, t) < 0 \Rightarrow \dot{S}(e_p, t) > 0 \Rightarrow \dot{S}(e_p, t) > 0 \]
\[ \Rightarrow P > P_{ref} \]

Then choose a vector suitable to decrease P.
\[ S_p(e_p, t) = 0 \]

Then choose a vector which does not significantly change the active power (15).

From the sliding mode control theory, robust sliding surfaces to control the P and Q variables with a relatively strong degree of one can be obtained considering proportionality to a linear combination of the errors of between the power references and the actual transmitted powers, respectively the state variables. Therefore, define the active power error and the reactive power error as the difference.
\[ e_p = P_{ref} - P \quad (8) \]
\[ e_Q = Q_{ref} - Q \quad (9) \]

Then, the robust sliding surfaces must be proportional to these errors, being zero after reaching sliding mode.
\[ S_p(e_p, t) = K_p(P_{ref} - P) = 0 \]
\[ S_q(e_Q, t) = K_q(Q_{ref} - Q) = 0 \]
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\[ \Rightarrow P > P_{ref} \]

Then choose a vector suitable to decrease P.
\[ S_p(e_p, t) = 0 \]

Then choose a vector which does not significantly change the active power (15).

The same procedure should be applied to the reactive power error applied to the reactive power error, to choose a vector from(4) and (11), and considering \( P_{ref} \) and in steady state, the following can be written the following Table. I. shows the Switching Combinations and Output Voltage / Input Current State-Space Vectors.
\[
\begin{align*}
\dot{S}(p,t) &= K_p \left( \frac{dP_{ref}}{dt} - \frac{dP}{dt} \right) = -K_p \frac{dP}{dt} = -K_p \frac{d(V_d I_d)}{dt} = -K_p V_d \frac{dI_d}{dt}, \\
\text{from (13) considering } V_d \text{ and } P_{ref} \text{ constants,} \\
\text{if } S_P(p,t) > 0, \text{ then it must be } S_P(p,t) > 0. \\
\text{From (14) if } K_p V_d \text{ is positive, then } \frac{dI_d}{dt} > 0 \text{, meaning that } P \text{ must increase from the equivalent model in dq coordinates present in (1) if the chosen vector has } V_d > V_{rod} - \omega L_d I_q + R_e I_d \text{ then } \frac{dI_d}{dt} > 0 \text{ then selected vector being suitable to increase the active power. Similarly from (5) and (13), with reactive power } Q_{ref} \text{ and } V_d \text{ in steady state.}
\end{align*}
\]

<table>
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<tr>
<th>Group</th>
<th>Name</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<th>(v_{BC})</th>
<th>(v_{CA})</th>
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<th>(i_b)</th>
<th>(i_c)</th>
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<td>(-i_C)</td>
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<td>(\delta_l)</td>
<td>(\sqrt{3}I_o)</td>
<td>(-\mu_o + 4\pi/3)</td>
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\(S_P\) must be positive if the equivalent model in dq coordinates present in (1) if the chosen vector has \(V_d > V_{rod} - \omega L_d I_q + R_e I_d\) then \(\frac{dI_d}{dt} > 0\) then selected vector being suitable to increase the active power. Similarly from (5) and (13), with reactive power \(Q_{ref}\) and \(V_d\) in steady state.

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**TABLE I**

**SWITCHING COMBINATIONS AND OUTPUT VOLTAGE/INPUT CURRENT STATE-SPACE VECTORS**

- Group I:
  - 1g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 2g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 3g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 4g: \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\), \(v_{AB} = -v_{ab}\)
  - 5g: \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\), \(v_{AB} = -v_{ab}\)
  - 6g: \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\), \(v_{AB} = -v_{ab}\)

- Group II:
  - 1g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 2g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 3g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 4g: \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\), \(v_{AB} = -v_{ab}\)
  - 5g: \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\), \(v_{AB} = -v_{ab}\)
  - 6g: \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\), \(v_{AB} = -v_{ab}\)

- Group III:
  - 1g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 2g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
  - 3g: \(v_{AB} = -v_{ab}\), \(v_{BC} = -v_{bc}\), \(v_{CA} = -v_{ca}\)
\[ \dot{s}(q, t) = K_q \left( \frac{dP_{\alpha\beta}}{dt} - \frac{dQ_{\alpha\beta}}{dt} \right) = -K_q \frac{dQ_{\alpha\beta}}{dt} = -K_q \frac{d(-V_d I_d)}{dt} = -K_q V_d \frac{dI_q}{dt} \]

From (13), if \( S_q(e_Q, t) > 0 \) then \( S_q(e_Q, t) < 0 \), which still implies \( \frac{dq}{dt} > 0 \), meaning that \( \frac{dI_q}{dt} \) must increase. Also, from (15) if \( k_2 V_d \left( \frac{dI_q}{dt} \right) < 0 \) which means that if \( k_2 V_d \) is positive then \( \frac{dI_q}{dt} \) must be negative. Considering the \( I_q \) current dynamics written in \( dq \) coordinates (2) then, to ensure the reaching condition, the chosen vector must have

\[ V_{ld} < V_{roq} + \omega L_2 I_d + R_2 I_q \]

To guarantee \( \frac{dI_q}{dt} < 0 \), meaning that the voltage vector has a \( q \) component suitable to increase the reactive power. Should be transformed to \( \alpha\beta \) coordinates \( S_\alpha(e_p, t) \) and \( S_\beta(e_Q, t) \) should be transformed to \( \alpha\beta \) coordinates \( S_\alpha(e_p, t) S_\beta(e_Q, t) \).

If the control errors and are quantized using two hysteresis Comparators, each with three levels (and) nine output voltage error combinations are obtained. If a two-level comparator is used to control the shunt reactive power, as discussed in next subsection, 18 error combinations will be defined, enabling the Selection of 18 vectors. Since the three zero vectors have a minor influence on the shunt reactive power control, selecting one out 18 vectors is adequate. As an example, consider the case of and Then, and imply that and. According to Table I, output voltage vectors depend on the input voltages (sending voltage), so to choose the adequate output voltage vector, it is necessary to know the input voltages location [Fig. 4(a)]. Suppose now that the input voltages are in sector [Fig. 4(b)], then the vectors to be applied should be 9 or 7. The final choice between these two depends on the matrix reactive power controller result, discussed in the next subsection. Using the same reasoning for the remaining eight active and reactive power error combinations and generalizing it for all other input voltage sectors, Table II is obtained. These \( P, Q \) controllers were designed based on control laws not dependent on system parameters, but only on the errors of the controlled output to ensure robustness to parameter variations or operating conditions and allow system order reduction, minimizing response times. The same procedure should be applied to the reactive power error. To choose a vector, from (4) and (12), and considering \( P_{\text{ref}} \) and \( V_{\text{ref}} \) in steady state, the following can be written. The following Table II shows the state-space vectors selection for different error combination.

**TABLE II**

<table>
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<th>( C_\alpha )</th>
<th>( C_\beta )</th>
<th>( V_i )</th>
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<th>12; 1</th>
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C. Direct Control of Matrix Converters Input Reactive Power

In addition, the matrix converter UPFC can be controlled to ensure a minimum or a certain desired reactive power at the matrix converter input. Similar to the previous considerations, since the voltage source input filter (Fig. 3) dynamics (6) has a strong relative degree of two [25], then a suitable sliding surface (19) will be a linear combination of the desired reactive power error and its first-order time derivative.

\[
\dot{S}(e_Q, t) = (Q_{ref} - Q_i) + K_{qi} \frac{d(Q_{ref} - Q_i)}{dt}
\]

The time derivative can be approximated by a discrete time difference, as has been chosen to obtain a suitable witching frequency, since as stated before, this sliding surface. From (17), it is seen that the control input, the iq matrix input current, must have enough amplitude to impose the adequate matrix input current vector that imposes the needed sign of the matrix input current, must have enough amplitude, (16) and (17) are used to establish the criteria (18) to choose the adequate matrix input current vector that imposes the needed sign of the matrix input-phase current related to the output-phase currents.

IV. IMPLEMENTATION OF THE DPC-MC AS UPFC

As shown in the block diagram (Fig. 6), the control of the instantaneous active and reactive powers requires the measurement of voltages and output currents necessary to calculate and sliding surfaces. The output currents measurement is also used to determine the location of the input currents component. The control of the matrixconverter input reactive power requires the input currents measurement to calculate. At each time instant, the most suitable matrix vector is chosen upon the discrete values of the sliding surfaces, using tables derived from Tables II and III for all voltage sectors. A simplified power transmission network of DPC technique applied to the three phase Matrix Converter (MC) operated as UPFC is presented in Fig. 1, is used for this study.

<table>
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<th>(C_{x2})</th>
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Fig.5. (a) Output currents and their corresponding sector (b) Input current state-space vectors

The sliding mode is reached when vectors applied to the converter have the necessary current amplitude to satisfy stability conditions. Therefore, to choose the most adequate vector in the chosen reference frame, it is necessary to know the output currents location since the input current depends on the output currents (Table I). Considering that the \(-x\) axis location is synchronous with the input voltage (i.e., reference frame depends on the input voltage location), the sign of the matrix reactive power can be determined by knowing the location of the input voltages and the location of the output currents (Fig. 5). From (17), it is seen that the control input, the matrix input current must have enough amplitude to impose the sign of the sliding surface. Therefore, to choose the most suitable matrix vector in the chosen reference frame, it is necessary to know the output currents location since the input current depends on the output currents (Table I).
The performance of the proposed direct control system was evaluated with a detailed simulation model using the MATLAB/Simulink. The load power is 1.5kW (1 p.u.) and transmission lines 1 and 2 are simulated as inductances L1=12 mH, L2 =15 mH, and series resistances R1=R2 = 0.2 Q, respectively for line 1 and 2. Sliding mode DPC gains are KP = KQ = KQi = 1 selected to ensure the highest switching frequencies around 2.5 kHz. Simulation results of the active and reactive direct power UPFC controller are obtained from the step response to changes in Pref and Qref references (Δ Pref and Δ Qref). Fig. 7(a) and (b) shows, respectively, the simulation results for the active and reactive power step response (Δ Pref = +0.4 p.u. and Δ Qref = +0.2 p.u.) and shunt reactive power, considering initial reference values: Pref = 0.4 p.u., Qref = 0.2 p.u., and Qref = -0.07 p.u. Both results clearly show that there is no cross-coupling between active and reactive power.

A. Waveforms for without matrix converter

Fig. 7. (a)
VI CONCLUSION

The proposed UPFC is able to control the full range of power flow and the power coefficient as is a conventional power flow controller. A UPFC based on a matrix converter is suitable for application where supply voltages are symmetrical. Presented simulation and experimental resultsshow that active and reactive power flow can be advantageous controlled by using the proposed DPC. Results show no steady-state errors, no cross-coupling, insensitivity to no modeled dynamics and fast response times, thus confirming the expected performance of the presented nonlinear DPC methodology.

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REFERENCES


