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Performance Analysis of Matrix Converter Based UPFC using MATLAB (Simulink)

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Abstract: In this paper, the Unified Power Flow Controller (UPFC) using a matrix converter is studied.Matrix Converter (MC) is mostly useful in high power energy generation system like wind energy, solar energy, Unified Power Quality Control (UPQC) systems. Such circuits are easily adaptable where critical power situation occurs. Moreover these types of circuits are versatile with less component and low power loss capability.UPFC enables the operation of transmission network near their maximum ratings by enforcing power flow through well defined lines. The existence of a dc capacitor bank originates additional losses, decreases the converter lifetime and increases its weight, cost and volume; this is removed in the proposed controller. The theoretical principles of direct power control (DPC) based on sliding mode control are established for a MC based UPFC dynamic model including the input filters. The 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.
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1.0 INTRODUCTION

In recent years, efficient control of AC signals in terms of voltage and frequency is much required due to technology advancement in industries. In past decades such controlling techniques were tedious and complex, the voltage and frequency could not vary simultaneously. So a less complex circuit with low loss and better output is mandatory. Among most of the converter in AC-AC converters, matrix converter is one of better converter due to the versatile nature of the converter [6]. Matrix converter is an alternative to AC-DC-AC converter which uses less number of switches with unique control.The matrix converter is a forced commutated single stage converter with an array of mxn bidirectional power switches connected directly from m-phase input to n-phase output produce variable output voltage with unrestricted frequency. The matrix converter comes just for the replacement of cycloconverter. The matrix converter output can be obtained by proper modulation technique. Since matrix converter uses only switches it transfer the energy without DC-link and large energy storage elements. The key feature in a MC, it is the fully controlled four quadrant operation due to bidirectional switch, which allows high frequency operation.

Also, the developments of high power semiconductor devices with fast control features have given birth to several Flexible AC Transmission Systems (FACTS) controllers [13]. Flexible AC Transmission Systems (FACTS) devices have gained big attraction today. Because these can be used to increase power system operation, flexibility and controllability to enhance system stability and better utilization of existing power system operation [14].These days, Unified Power Flow Control (UPFCs) is the one of the most powerful flexible ac transmission systems (FACTS) devices. The UPFC is nothing but the combination of a static synchronous compensator (STATCOM) and a static synchronous series

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compensator (SSSC) which shares a common dc capacitor link. The minimum energy storage capability of matrix allows independent reactive control on the UPFC shunt and series converter sides.

In the last few decades, an increasing interest in new converter types, capable of performing the same functions but with reduced storage needs, has arisen. The two converters and the capacitor in the UPFC's structure are replaced with a dual-bridge matrix converter. Matrix converters (MCs) allow the direct ac- ac power conversion without dc energy storage links, matrix converter is a bidirectional power flow converter that uses semi converter switches arranged in the form of matrix array [2]. Therefore, the matrix converter based unified power flow controller (MC- UPFC) has reduced cost, capacitor power losses and volume with higher reliability. Conventional UPFC controllers do not guarantee robustness the dependence of the matrix converter output voltage on the modulation coefficient was investigated, concluding that MC-UPFC is able to control the full range of power flow. Recent nonlinear approaches enabled better tuning of PI controller parameters. Still, there is room to further improve the dynamic response of UPFCs, using nonlinear robust controllers.In the last few years, direct power control techniques have been used in many power applications, due to their simplicity and good performance [7].

2.0 LITERATURE SURVEY

The introduction of power transistors for implementing the bidirectional switches made the matrix converter topology more attractive[6]. A conceptually different control technique based on the "fictitious dc link" idea was introduced by Rodriguez In 1983. The matrix converter is a single-stage converter which has an array m X n of bidirectional power switches to connect, directly, an m-phase voltage source to an n-phase load. Defining the switching function of a single switch as the 3 x 3 matrix converter has 27 possible switching states.

The modulation methods based on the Venturini approach are known as "direct methods," while those based on the "fictitious dc link" are known as "indirect methods." Since a well known space vector pulse width modulation (SVPWM) method for a matrix converter has been proposed. A different concept of SVPWM method was introduced as indirect method where the matrix converter is interpreted as a cascade connection of two converters, a PWM converter and a PWM inverter [2]. To simplify the modulation procedure carrier based modulation technique was proposed, which was mathematically proven as SVPWM method. In the mean time some researchers on the PWM method concentrated in reduction of the switching loss and the improvement of the output current quality have been introduced [2]. Another method using the predictive technique was proposed in [3]. The idea was to predict switching losses for every switching state, and then, selected the optimum state based on evaluationcriterion. As a way to improve the output current characteristics, research on the arrangement of the zero vector was also introduced.Filters must be used at the input of the matrix converters to reduce the switching frequency harmonics present in the input current.

In [5], a matrix converter-based UPFC (MC-UPFC) for power transmission networks is used to control the P and Q power flow in a transmission line. This paper presents the design and comparison of linear and nonlinear (sliding mode) controllers based on suitable power system models. Three different types of controllers are designed and tested: (1) Proportional Integral (PI) linear controllers obtained from a linear P and Q steady-state power UPFC linearized model, around an operating point, using a modified Venturini high-frequency MC pulse width modulator. (2) Decoupled Linear Controllers (DLC) designed by inverse dynamics linearization, allowing the elimination of the cross coupling effect between P and Q power controllers. (3) DPC, which have been successfully used in power applications, owing to its simplicity and good performance.This control method based on sliding-mode control technique allows real-time selection of adequate state-space vectors to control input and output variables. These controllers are insensitive to power system nonlinearity, presenting robust behavior to parameter variations and disturbances [7].

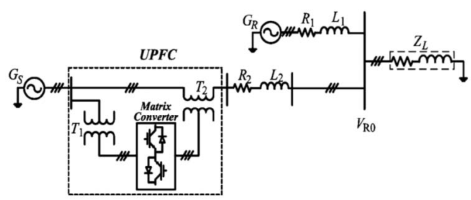

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Fig. 1. Transmission network with matrix converter UPFC.

A simplified power transmission network using the proposed matrix converter UPFC is presented in Fig. 1, where V_S and V_R are respectively the sending-end and receiving-end sinusoidal voltages of the G_S and G_R generators feeding load Z_L. The matrix converter is connected to transmission line 2, represented as a series inductance with series resistance (L_2 and R_2), through coupling transformers T_1 and R_2.

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. Also, the matrix converter is considered ideal and represented as a controllable voltage source, with amplitude V_C and phase ρ. In the equivalent circuit, V_{R0} is the load bus voltage. The DPC-MC controller will treat the simplified elements as disturbances.

Considering a symmetrical and balanced three-phase system and applying Kirchhoff laws to the three- phase equivalent circuit (Fig. 2), the ac line currents are obtained in dq coordinates

$$\frac{dI_d}{dt} = \omega I_q - \frac{R_2}{L_2} I_d + \frac{1}{L_2}(V_{Ld} - V_{R0d}) \qquad - (1)$$

$$\frac{dI_q}{dt} = \omega I_d - \frac{R_2}{L_2} I_q + \frac{1}{L_2}(V_{Lq} - V_{R0q}) \qquad - (2)$$

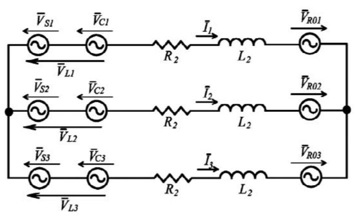

Fig. 2. Three-phase equivalent circuit of the matrix UPFC and transmission line.

The active and reactive power of sending end generator are given in dq coordinates by

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad - (3)$$

Assuming V_{R0d} and $V_{Sd} = V_d$ 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

$$P = V_d I_d \qquad - (4)$$

$$Q = -V_d I_q \qquad -(5)$$

Based on the desired active and reactive power (P_{ref}, Q_{ref}), reference currents (I_{dref}, I_{qref}) can be calculated from (4) and (5) for current controllers. However, allowing P, Q actual powers are sensitive to errors in the V_d, V_q values.

1.1 Matrix Converter Output Voltage and Input Current Vectors

A diagram of the UPFC system (Fig. 3) includes the three-phase shunt input transformer (with windings T_a, T_b, T_c), the three-phase series output transformer (with windings T_A, T_B, T_C), and the three-phase matrix converter, represented as an array of nine bidirectional switches S_{kj} 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. The three-phase (lC_r) input filter is required to re-establish a voltage-source boundary to the matrix converter, enabling smooth input currents.

Applying dq coordinates to the input filter state variables presented in Fig. 3 and neglecting the effects of the damping resistors, the following equations are obtained:

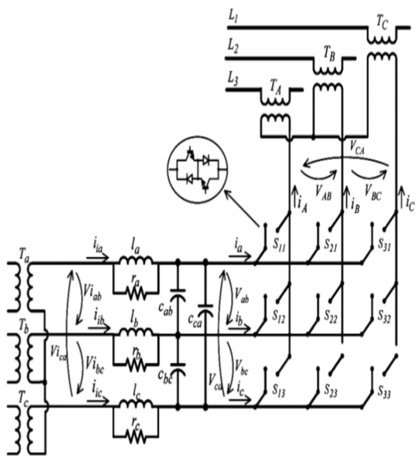

Fig.3 Transmission network with matrix converter UPFC

$$\begin{cases} \dfrac{di_{id}}{dt} = \omega i_{iq} - \dfrac{1}{2l} V_d - \dfrac{1}{2\sqrt{3}l} V_q + \dfrac{1}{l} V_{id} \\ \dfrac{di_{iq}}{dt} = -\omega i_{id} + \dfrac{1}{2\sqrt{3}l} V_d - \dfrac{1}{2l} V_q + \dfrac{1}{l} V_{iq} \\ \dfrac{dV_d}{dt} = \omega V_q - \dfrac{1}{2\sqrt{3}C} i_{iq} + \dfrac{1}{2C} i_{id} - \dfrac{1}{2C} i_d + \dfrac{1}{2\sqrt{3}C} i_q \\ \dfrac{dV_q}{dt} = -\omega V_d - \dfrac{1}{2\sqrt{3}C} i_{id} + \dfrac{1}{2C} i_{iq} - \dfrac{1}{2\sqrt{3}C} i_d - \dfrac{1}{2C} i_q \end{cases} \qquad -(6)$$

where V_{id}, V_{iq}, i_{id}, i_{iq} represent, respectively, input voltages and input currents in dq components (at the shunt transformer secondary) and V_d, V_q, i_d, i_q are the matrix converter voltages and input currents in dq components, respectively.

Assuming ideal semiconductors, each matrix converter bidirectional switch S_{kj} (kj є {1,2,3}) can assume two possible states: "S_{kj} =1" if the switch is closed or " S_{kj} =0" if the switch is open. The nine matrix converter switches can be represented as a 3 × 3 matrix (7)

$$S=\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \quad - (7)$$

The matrix converter topological constraints implies

$\sum_{j=1}^{3} S_{kj} = 1$

Based on (7), the relationship between load and input voltages can be expressed as

$$[V_A \quad V_B \quad V_C]^T = S\,[v_a \quad v_b \quad v_c]^T \quad - (8)$$

The input phase currents can be related to the output phase current using the transpose of using the transpose of matrix S

$$[i_a \quad i_b \quad i_c]^T = S^T [I_A \quad I_B \quad I_C]^T \quad -(9)$$

From the 27 possible switching patterns, time-variant vectors can be obtained representing the matrix output voltage and current in αβ co-ordinates.

The active and reactive power DPC-MC will select one of these 27 vectors at any given time instant.

2.0 DIRECT POWER CONTROL OF MC-UPFC

2.1 Line Active and Reactive Power Sliding Surfaces

The DPC controllers for line power flow are here derived based on the sliding mode control theory.

From Fig. 2, in steady state, V_d is imposed by source. From (1) and (2), the transmission-line currents can be considered as state variables with first-order dynamics dependent on the sources and time constant of impedance $L_2/\ R_2$ .Therefore, transmission-line active and reactive powers present first-order dynamics and have a strong relative degree of one, since from the control viewpoint, its first time derivative already contains the control variable (the strong relative degree generally represents the number of times the control output variable must be differentiated until a control input appears explicitly in the dynamics).

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 the state variables. Therefore, define the active power error e_P and the reactive power error e_Q as the difference between the power references P_{ref} and Q_{ref} the actual transmitted powers 'P, Q' respectively.

$$e_P = P_{ref} - P \quad - (10)$$

$$e_Q = Q_{ref} - Q \quad - (11)$$

Thus robust sliding surfaces $S_P(e_P, t)$ and $S_Q(e_Q, t)$ must be proportional to these errors being zero after reaching sliding mode.

$$S_P(e_P, t) = k_P(P_{ref} - P) = 0 \quad - (12)$$

$$S_Q(e_Q, t) = k_Q(Q_{ref} - Q) = 0 \quad -(13)$$

The proportional gain k_P and k_Q are chosen to impose appropriate switching frequencies.

2.2 Line Active and Reactive Power Direct switching laws:

The DPC uses a nonlinear law, based on the errors e_P and e_Q to select in real time the matrix converter switching states. 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 (14) and (15) must be verified.

$$S_P(e_P, t)\,\dot{S}_Q(e_Q, t) < 0 \quad - (14)$$

$$S_Q(e_Q, t)\,\dot{S}_Q(e_Q, t) < 0 \quad - (15)$$

These conditions mean that if $S_P(e_P, t) > 0$, then the $S_P(e_P, t)$ value must be decreased, meaning that its time derivative should be negative ($\dot{S}_P(e_P, t) < 0$). Similarly, if $S_P(e_P, t) < 0$, then $\dot{S}_P(e_P, t) > 0$.

According to (12) and (14), the criteria to choose the matrix vector should be

1. If $S_P(e_P, t) > 0 \Rightarrow \dot{S}_P(e_P, t) < 0 \Rightarrow P < P_{ref}$ then choose a vector suitable to increase P.
2. If $S_P(e_P, t) < 0 \Rightarrow \dot{S}_P(e_P, t) > 0 \Rightarrow P > P_{ref}$ then choose a vector suitable to decrease P.
3. If $S_P(e_P, t) = 0$ then choose a vector which

does not significantly change the active power.

The same procedure should be applied to the reactive power error.

2.3 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 dynamics has a strong relative degree of two, then a suitable sliding surface S_{Q_i} (e_{Q_i} , t) will be a linear combination of the desired reactive power error $e_{Q_i} = Q_{i_{ref}}$ - Q_i and its first order time derivative.

$$S_{Q_i}(e_{Q_i}, t) = (Q_{i_{ref}} - Q_i) + K_{Q_i}\frac{d}{dt}(Q_{i_{ref}} - Q_i) \quad \text{-(16)}$$

The time derivative can be approximated by a discrete time difference, as K_{Q_i} has been chosen to obtain a suitable switching frequency, since as stated before, this sliding surface needs to be quantized only in two levels and using one hysteresis comparator.

To fulfill a stability condition consider the input filter dynamics

$$\dot{S}_{Q_i}(e_{Q_i}, t) = -V_{i_d}\left(\frac{di_q}{dt} - K_{Q_i}\frac{d^2 i_q}{dt^2}\right) \quad \text{-(17)}$$

It is seen that the control input, the i_q matrix input current, must have enough amplitude to impose the sign of $\dot{S}_{Q_i}$ (e_{Q_i} , t). Supposing there is enough i_q amplitude (16) and (17) are used to establish the criteria (12) to choose the adequate matrix input current i_q vector 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

1. If S_{Q_i} (e_{Q_i} , t) > 0 => ($\dot{S}_{Q_i}$, t)< 0, then select vector with current i_q < 0 to increase Q_i
2. If S_{Q_i}(e_{Q_i}, t) <0 => $\dot{S}_{Q_i}$ (e_{Q_i} , t) > 0, then select vector with current i_q > 0 to decrease Q_i

Hence above are the governing equations of Direct Power Control (DPC) of MC-UPFC to control line active and reactive power sliding surface, and direct control of matrix converter input reactive power.

3.IMPLEMENTATION OF DPC-MC AS UPFC:

As shown in the block diagram (Fig. 4), the control of the instantaneous active and reactive powers requires the measurement of G_S voltages and output currents necessary to calculate S_α (e_P , t) and S_β (e_Q , t) and sliding surfaces.

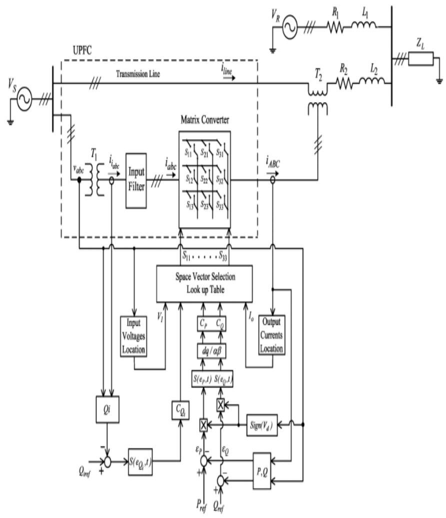

Fig. 4 Control scheme of direct power control of the three-phase matrix converter operating as a UPFC

The output currents measurement is also used to determine the location of the input currents component. The control of the matrix converter input reactive power requires the input currents measurement to calculate S_{Qi} (e_{Qi} , t). At each time instant, the most suitable matrix vector is chosen upon the discrete values of the sliding surfaces.

4.SIMULATIONS RESULTS

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 L_1 =12 mH L_2 =15 mH, and series resistances R_1 = R_2 = 0.2 Ω, respectively for line 1 and 2. Sliding mode DPC gains are K_P = K_Q = K_{Qi} =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 P_{ref} and Q_{ref} references (Δ P_{ref} and Δ Q_{ref}).

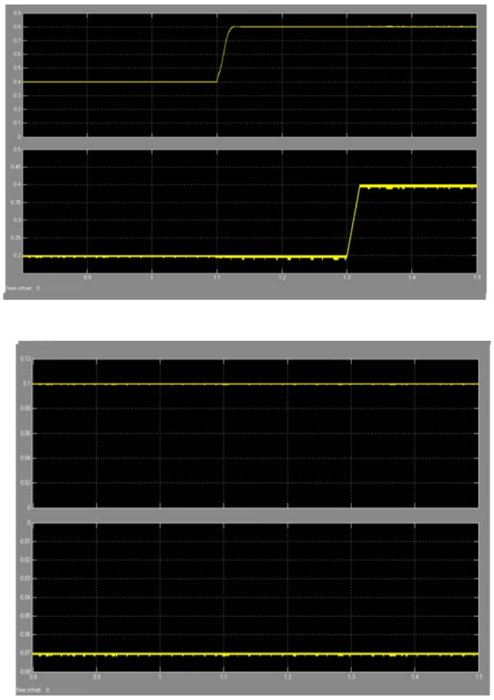

Fig 5 (a), (b): Active and reactive series power response and reactive shunt power, for P and Q steps

Fig. 5(a) and (b) shows, respectively, the simulation results for the active and reactive power step response (Δ P_{ref} = +0.4 p.u. and Δ Q_{ref} =+ 0.2 p.u.) and shunt reactive power, considering initial reference values: P_{ref} = 0.4 p.u., Q_{ref} = 0.2 p.u., and Q_{ref} = -0.07 p.u. Both results clearly show that there is no cross-coupling between active and reactive power.

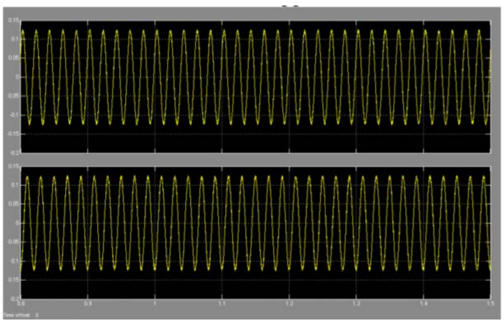

Fig 6 (a), (b): Line currents (i_A, i_B) and input matrix converter currents (i_b, i_c) p.u.:Simulation results.

The results of Fig.6(a) and (b) show line and input matrix converter currents in steady state, for P_{ref} = 0.4 p.u., Q_{ref} = 0.2 p.u., and Q_{ref} = - 0.07 p.u. Currents are almost sinusoidal with small ripple content.

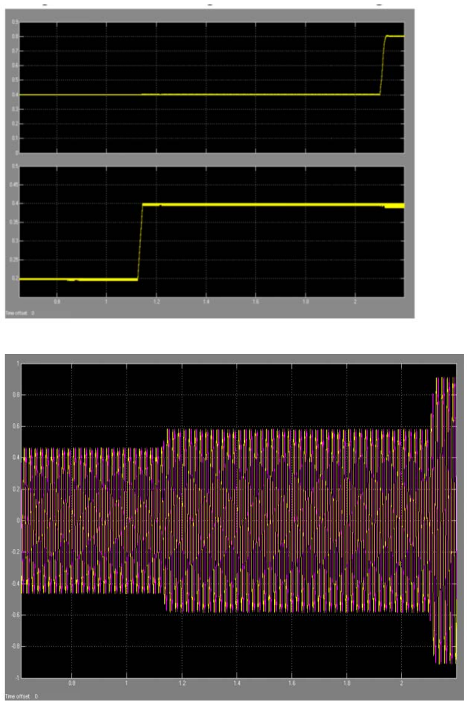

Fig. 7(a),(b): Active and reactive power response and line currents for a P and Q step change Direct power controller simulations

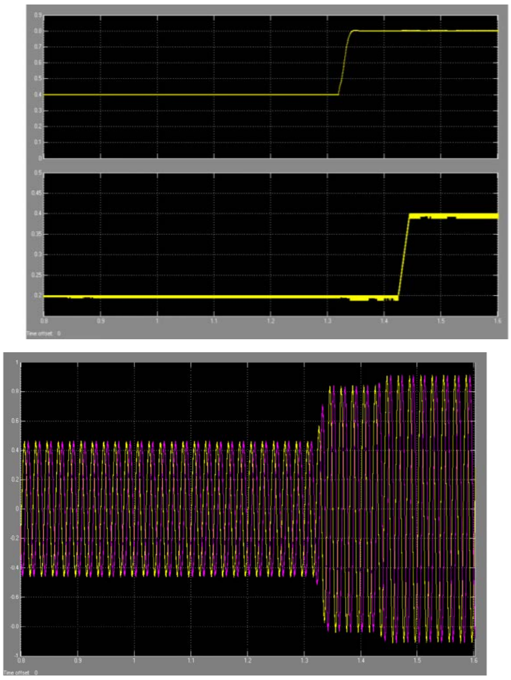

Fig. 8 (a), (b) : Active and reactive power response and line currents for a P and Q

DPC simulation results presented in Fig. 7(a) and (b), showing the claimed DPC faster dynamic response to step active and reactive power reference change.

DPC controller ability to operate at lower switching frequencies, the DPC gains were lowered and the input filter parameters were changed accordingly (r=25 Ω, l=5.9 mH C=12.6 μF) to lower the switching frequency to nearly 1.4 kHz. The results (Fig. 8) also show fast response without cross coupling between active and reactive power. This confirms the DPC-MC robustness to input filter parameter variation, the ability to operate at low switching frequencies, and insensitivity to switching nonlinearity.

5.0 CONCLUSIONS

The contribution of this paper is to propose a nonlinear direct power controller, for matrix converters connected to power transmission lines as UPFCs. Recent nonlinear approaches use better tuning control like PI control method. So tuning of PWM using these techniques adopted to meet the requirement. Still, there is possibility of further improvement in the dynamic response of UPFCs, using nonlinear robust controllers. Sliding mode-based direct power control Matrix Converter (DPC-MC) controllers have zero steady-state errors and no overshoots, good tracking performance, and fast dynamic responses. When compared to linear PI controller Slide mode control is simpler to implement and require less processing power.

Presented simulation and experimental results show that active and reactive power flow can be advantageously controlled by using the proposed DPC. Results show no steady-state errors, no cross- coupling, insensitivity to non modeled dynamics and fast response times, thus confirming the expected performance of the presented nonlinear DPC methodology. Obtained results show that DPC is a strong nonlinear control candidate for line active and reactive power flow.

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