A Novel Control Strategy for Direct Power Control with MC-Based UPFC

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Abstract: *This paper presents a novel control strategy for direct power control with MC-based UPFC. In general power control techniques are two methods; first one is a well-known method of indirect active and reactive power control is based on current vector orientation with respect to the line voltage vector [voltage-oriented control (VOC)]. Another less known method based on instantaneous direct active and reactive power control is called direct power control (DPC).A new simple method of line voltage sensor less DPC with constant switching frequency using space-vector modulation (DPC-SVM) is presented. DPC is based on the instantaneous active and reactive power control loops. Therefore, the key point of the DPC implementation is a correct and fast estimation of the active and reactive line power. A direct power control (DPC) for three-phase matrix converters operating as unified power flow controllers (UPFCs). 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. The simulation result of MC-based UPFC 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. Finally proposed Fuzzy controller forces the amplitude of the output current space vector to be constant so that the output current is free of harmonic.*

Keywords: *Direct power control (DPC), matrix converter (MC), unified power-flow controller (UPFC), space vector modulation (SVM).*

I. INTRODUCTION

The AC–AC power converters known as matrix converters contain an array of bi-directional semiconductor switches that allow the connection of all the input voltage lines to all the output voltages. These bi-directional switches result from the association of power semiconductors consisting of a pair of devices with turn-off capability, usually insulated gate bipolar transistors (IGBTs), in either a common collector or a common emitter back-to-back arrangement. Usually, Each IGBT has an anti-parallel diode that may be avoided if reverse blocking IGBTs are used. Matrix converters, also known as all silicon converters, present the advantage of not needing an intermediate energy storage link. However, its absence implies input/ output coupling, thus increasing the difficulty to define adequate control strategies. Nevertheless, over the years some pulse width modulation (PWM) techniques have been developed, although the first were mainly concerned with the output voltage control, neglecting the waveform quality of the input currents. In the 1980s, Alesina and Venturini introduced the matrix converter high frequency PWM approach enabling low harmonic contents for both output voltages and input currents and an output/input Voltage ratio of 0.86. Since then, other control approaches such as space vector modulation (SVM) [7] have been studied. The SVM technique, used for most three-phase converters, is based on the representation of output voltages or input currents resulting from all allowable matrix converter switching combinations, as vectors in the complex plane. It has the advantage of allowing a better selection of the required voltage and current vectors, simplifying control algorithms and providing maximum voltage transfer ratio without the need to add third harmonic modulator components.

The matrix converter direct control is achieved using the Sliding mode control technique [7], based on the space vector representation, to allow on-line the control of output voltages and input power factor. Sliding mode is designed to guarantee the on-line compensation of the displacement factor introduced by the input filter, a subject not addressed in previous publications. Unified power-flow controllers (UPFC) enable the operation of power transmission networks near their maximum ratings, by enforcing power flow through well-defined lines. These days, UPFCs are one of the most versatile and powerful flexible ac transmission systems (FACTS) devices [1]. L.Gyugyi [2, 3] proposed concept of The UPFC results from the combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) that shares a common dc capacitor link.

The existence of a dc capacitor bank originates additional losses, decreases the converter lifetime, and increases its weight, cost, and volume. . The existence of a dc capacitor bank originates additional losses, decreases the converter lifetime, and increases its weight, cost, and volume. 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 .These converters are capable of performing the same ac/ac conversion, allowing bidirectional power flow, guaranteeing near sinusoidal input and output currents, voltages with variable amplitude, and adjustable power factor[6]. Conventional UPFC controllers do not guarantee robustness and. In, 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. In the last few years, direct power control techniques have been used in many power applications, due to their simplicity and good performance. A matrix converter- based UPFC [5] power transmission network using matrix converter is proposed in section II. In order to design UPFCs, presenting robust behavior to parameter variations and to disturbances, the proposed DPC-MC control method, in section III, is sliding mode-control techniques based on space vector modulation, allowing the real-time selection of adequate matrix vectors to control input and output electrical power. The Fuzzy controller for matrix converter system is proposed in section III to improve its quality of output. Fuzzy controller forces the amplitude of the output current space vector to be constant so that the output current is free of harmonic. The steady-state behavior of the proposed DPC-MC P, Q control method is evaluated and discussed using detailed simulations implementation (section IV). Simulation results obtained with the DPC for matrix converter-based UPFC technology show decoupled series active and shunt/series reactive power control, zero steady-state error tracking, and fast response times, presenting faultless steady-state responses.

II. MODELING OF THE UPFC POWER SYSTEM

1. General Architecture

A simplified power transmission network using the proposed matrix converter UPFC is presented in Fig.1, where Vs and Vr are, respectively, the sending-end and receiving-end sinusoidal voltages of the and generators feeding load. The matrix converter is connected to transmission line 2, represented as a series inductance with series resistance (L2 and R2), through coupling transformers T_1 and T_2. Fig.2 shows the simplified three-phase equivalent circuit of the matrix UPFC transmission system model in [4]. 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 and phase. In the equivalent circuit, 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 coordinates

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

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

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

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

Assuming and as constants and a rotating reference frame synchronized to the source so that 0, active and reactive power and 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, reference currents can be calculated from (4) and (5) for current controllers. However, allowing actual powers are sensitive to errors in the values.

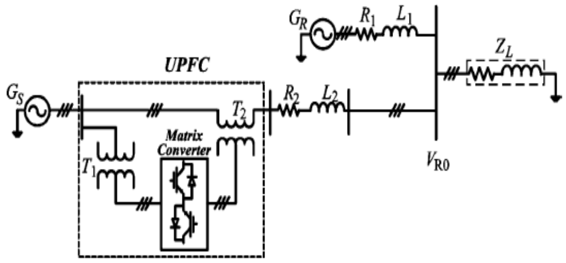

Fig 1: Transmission network with matrix converter UPFC.

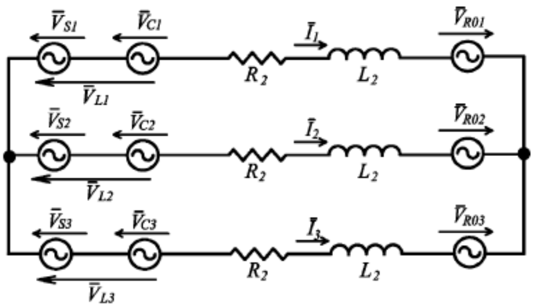

Fig 2: Three-phase equivalent circuit of the matrix UPFC and transmission line

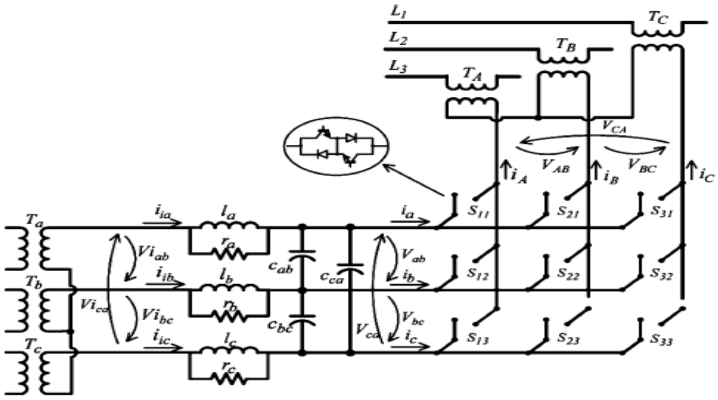

Fig 3: Transmission network with matrix converter UPFC.

2. 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), the three-phase series output transformer (with windings) and the three-phase matrix converter, represented as an array of nine bidirectional switches 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 input filter is required to re-establish a voltage-source boundary to the matrix converter, enabling smooth input currents. 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

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

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

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 are the matrix converter voltages and input currents in components, respectively. Assuming ideal semiconductors, each matrix converter bidirectional switch can assume two possible states: "Skj = 1" if the switch is closed or "Skj = 0" if the switch is open. The nine matrix converter switches can be represented as a 3x3 matrix (7). The matrix converter topological constraint implies. Based on (7), the relationship between load and input voltages can be expressed as (8) The input phase currents can be related to the output phase currents (9), using the transpose of matrix S From the 27 possible switching patterns, time-variant vectors can be obtained (Table I) representing the matrix output voltages and input currents in αβ coordinates, and plotted in the αβ frame [Fig.4 (b)].

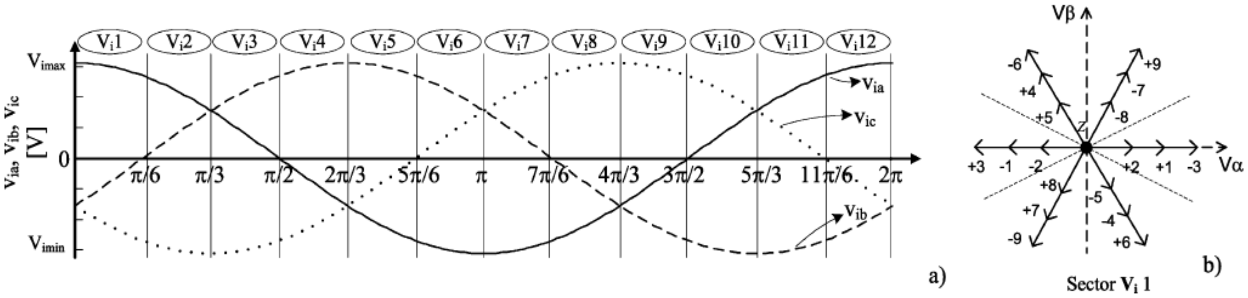

Fig 4: (a) Input voltages and their corresponding sector. (b) Output voltage state-space vectors when the input voltages are located at sector vi1.

The matrix converter topological constraints implies $\sum_{j=1}^{3} S_{kj} = 1.$

$$[v_A \quad v_B \quad v_C]^T = \boldsymbol{S}[v_a \quad v_b \quad v_c]^T \quad (8)$$

$$[i_a \quad i_b \quad i_c]^T = \boldsymbol{S}^T[i_A \quad i_B \quad i_C]^T \quad (9)$$

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

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

Group	Name	A	B	C	v_{AB}	v_{BC}	v_{CA}	i_a	i_b	i_c	V_o	δ_o	I_i	μ_i
	1g	a	b	c	v_{ab}	v_{bc}	v_{ca}	i_A	i_B	i_C	v_i	δ_i	$\sqrt{3}i_o$	μ_o
	2g	a	c	b	$-v_{ca}$	$-v_{bc}$	$-v_{ab}$	i_A	i_C	i_B	$-v_i$	$-\delta_i+4\pi/3$	$\sqrt{3}i_o$	$-\mu_o$
I	3g	b	a	c	$-v_{ab}$	$-v_{ca}$	$-v_{bc}$	i_B	i_A	i_C	$-v_i$	δ_i	$\sqrt{3}i_o$	$-\mu_o+2\pi/3$
	4g	b	c	a	v_{bc}	v_{ca}	v_{ab}	i_C	i_A	i_B	v_i	$\delta_i+4\pi/3$	$\sqrt{3}i_o$	$\mu_o+2\pi/3$
	5g	c	a	b	v_{ca}	v_{ab}	v_{bc}	i_B	i_C	i_A	v_i	$\delta_i+2\pi/3$	$\sqrt{3}i_o$	$\mu_o+4\pi/3$
	6g	c	b	a	$-v_{bc}$	$-v_{ab}$	$-v_{ca}$	i_C	i_B	i_A	$-v_i$	$-\delta_i+2\pi/3$	$\sqrt{3}i_o$	$-\mu_o+4\pi/3$
	+1	a	b	b	v_{ab}	0	$-v_{ab}$	i_A	$-i_A$	0	$\sqrt{2/3}v_{ab}$	0	$\sqrt{2}i_A$	$-\pi/6$
	-1	b	a	a	$-v_{ab}$	0	v_{ab}	$-i_A$	i_A	0	$-\sqrt{2/3}v_{ab}$	0	$-\sqrt{2}i_A$	$-\pi/6$
	+2	b	c	c	v_{bc}	0	$-v_{bc}$	0	i_A	$-i_A$	$\sqrt{2/3}v_{bc}$	0	$\sqrt{2}i_A$	$\pi/2$
	-2	c	b	b	$-v_{bc}$	0	v_{bc}	0	$-i_A$	i_A	$-\sqrt{2/3}v_{bc}$	0	$-\sqrt{2}i_A$	$\pi/2$
	+3	c	a	a	v_{ca}	0	$-v_{ca}$	$-i_A$	0	i_A	$\sqrt{2/3}v_{ca}$	0	$\sqrt{2}i_A$	$7\pi/6$
	-3	a	c	c	$-v_{ca}$	0	v_{ca}	i_A	0	$-i_A$	$-\sqrt{2/3}v_{ca}$	0	$-\sqrt{2}i_A$	$7\pi/6$
	+4	b	a	b	$-v_{ab}$	v_{ab}	0	i_B	$-i_B$	0	$\sqrt{2/3}v_{ab}$	$2\pi/3$	$\sqrt{2}i_B$	$-\pi/6$
	-4	a	b	a	v_{ab}	$-v_{ab}$	0	$-i_B$	i_B	0	$-\sqrt{2/3}v_{ab}$	$2\pi/3$	$-\sqrt{2}i_B$	$-\pi/6$
II	+5	c	b	c	$-v_{bc}$	v_{bc}	0	0	i_B	$-i_B$	$\sqrt{2/3}v_{bc}$	$2\pi/3$	$\sqrt{2}i_B$	$\pi/2$
	-5	b	c	b	v_{bc}	$-v_{bc}$	0	0	$-i_B$	i_B	$-\sqrt{2/3}v_{bc}$	$2\pi/3$	$-\sqrt{2}i_B$	$\pi/2$
	+6	a	c	a	$-v_{ca}$	v_{ca}	0	$-i_B$	0	i_B	$\sqrt{2/3}v_{ca}$	$2\pi/3$	$\sqrt{2}i_B$	$7\pi/6$
	-6	c	a	c	v_{ca}	$-v_{ca}$	0	i_B	0	$-i_B$	$-\sqrt{2/3}v_{ca}$	$2\pi/3$	$-\sqrt{2}i_B$	$7\pi/6$
	+7	b	b	a	0	$-v_{ab}$	v_{ab}	i_C	$-i_C$	0	$\sqrt{2/3}v_{ab}$	$4\pi/3$	$\sqrt{2}i_C$	$-\pi/6$
	-7	a	a	b	0	v_{ab}	$-v_{ab}$	$-i_C$	i_C	0	$-\sqrt{2/3}v_{ab}$	$4\pi/3$	$-\sqrt{2}i_C$	$-\pi/6$
	+8	c	c	b	0	$-v_{bc}$	v_{bc}	0	i_C	$-i_C$	$\sqrt{2/3}v_{bc}$	$4\pi/3$	$\sqrt{2}i_C$	$\pi/2$
	-8	b	b	c	0	v_{bc}	$-v_{bc}$	0	$-i_C$	i_C	$-\sqrt{2/3}v_{bc}$	$4\pi/3$	$-\sqrt{2}i_C$	$\pi/2$
	+9	a	a	c	0	$-v_{ca}$	v_{ca}	$-i_C$	0	i_C	$\sqrt{2/3}v_{ca}$	$4\pi/3$	$\sqrt{2}i_C$	$7\pi/6$
	-9	c	c	a	0	v_{ca}	$-v_{ca}$	i_C	0	$-i_C$	$-\sqrt{2/3}v_{ca}$	$4\pi/3$	$-\sqrt{2}i_C$	$7\pi/6$
	z_a	a	a	a	0	0	0	0	0	0	0	-	0	-
III	z_b	b	b	b	0	0	0	0	0	0	0	-	0	-
	z_c	c	c	c	0	0	0	0	0	0	0	-	0	-

3. General Structure of Fuzzy System

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multi valued logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with UN sharp boundaries in which membership is a matter of degree. Every fuzzy system is composed of four principal blocks (Fig 5):

1. **Knowledge base** (rules and parameters for membership functions)
2. **Decision unit** (inference operations on the rules)
3. **Fuzzification interface** (transformation of the crisp inputs into degrees of match with linguistic variables)
4. **Defuzzification interface** (transformation of the fuzzy result of the inference into a crisp output)

In this simulation, we partitioned a space of input and output variables into 7 fuzzy subsets. They are presented by 7 membership functions as in the Table.V these functions are:

- Negative Big (NB)
- Negative Medium (NM)
- Negative Small (NS)
- Close to Zero (ZE)
- Positive Small (PS)
- Positive Medium (PM)
- Positive Big (PB)

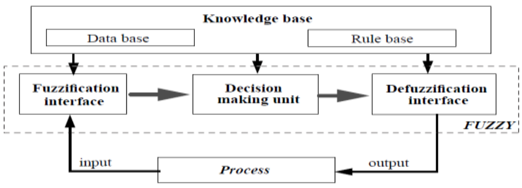

Fig 5: General structure of fuzzy inference system

The rule base that we can take the rule base proposed by Mamdani for the simulation of Fuzzy based DPC controller in [8]. These rules are shown in the Table V. The table is read in the following way, If the error is negative small (NS) **and** the change in error positive big (PB), **than** the control action is positive medium (PS). The inference method of Mamdani is max-min composition is chosen in the work to simplify the programming algorithm. After several trials has been made to select membership function. And finally it is decided to select triangular membership function. The fuzzy based DPC controller is used for ac-ac Matrix converter. The fuzzy controller forces the amplitude of the output current space vector to be constant so that the output current is free of harmonic.

TABLE V. Fuzzy controller rule base

Rule base for Fuzzy controller

		Change in error(ce)						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
E	**NB**	NB	NB	NM	NM	NS	NS	ZE
R	**NM**	NB	NM	NM	NS	NS	ZE	PS
R	**NS**	NM	NM	NS	NS	ZE	PS	PS
O	**ZE**	NM	NS	NS	ZE	PS	PS	PM
R	**PS**	NS	NS	ZE	PS	PS	PM	PM
(e)	**PM**	NS	ZE	PS	PS	PM	PM	PB
	PB	ZE	PS	PS	PM	PM	PB	PB

III. Direct Power Control of MC-UPFC

The matrix converter direct power control is achieved using the sliding mode control technique [7], based on the space vector representation, to allow on-line the control of output voltages and input power factor.DPC is based on the instantaneous active and reactive power control loops. This approach allows the design of the controller considering the converter and the dynamics of its associated LC filter. Together with the space vector representation technique, sliding mode allows the precise determination of switching times between the bi-directional switches, thus being appropriate to the nonlinear ON/OFF behavior of the matrix converter power semiconductors. As the switching occurs just in time, this technique guarantees fast response times and precise control actions, ensuring that the output voltages and the input currents track their references and making input power factor regulation independent of the input filter parameters. This feature has special interest in applications requiring unity input power factor, when feeding AC drives, or applications needing variable and accurate input power factor regulation, usually related to power quality enhancement. In DPC there are no internal current control loops and no PWM modulator block, because the converter switching states are selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power. Therefore, the key point of the DPC implementation is a correct and fast estimation of the active and reactive line power.

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. The Sliding mode control techniques present special interest for variable structure systems as they can use this property to successfully solve the control problem, guaranteeing the choice of the most appropriate control actions. Matrix converters are variable structure systems, as a result of the ON/OFF switching of their power semiconductors, but the design of sliding mode controllers and the choice of the most appropriate space vectors represent a though challenge, since the input and output variables are interdependent. In fact, according to Table 1, the output voltage vectors depend on the input (mains) voltages and the input current vectors depend on the output currents, assumed nearly sinusoidal, but dependent on the matrix converter output voltages. To overcome these problems, it will be necessary

1. To guarantee the adequate control of the output variables in order to use the current space vectors as defined in Table 1;
2. To consider the input/output power constraint.

From Fig.4, in steady state, V_d is imposed by source Vs 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. 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. From the sliding mode control theory [7], 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 Pref, Qref and the actual transmitted powers P, Q respectively

$$e_P = P_{\text{ref}} - P \qquad (10) \qquad S_P(e_P,t) = k_P(P_{\text{ref}} - P) = 0 \qquad (12)$$

$$e_Q = Q_{\text{ref}} - Q. \qquad (11) \qquad S_Q(e_Q,t) = k_Q(Q_{\text{ref}} - Q) = 0. \qquad (13)$$

Then, the robust sliding surfaces Sp (e_p ,t) and S_Q (e_Q,t) must be proportional to these errors, being zero after reaching sliding mode are shown above in Eq. (12&13). The proportional gains K_P and K_Q are chosen to impose appropriate switching frequencies.

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 (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 (14) and (15) must be verified

$$S_P(e_P,t)\dot{S}_P(e_P,t) < 0 \qquad (14)$$

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

These conditions mean that if Sp (e_p ,t) > 0 , then the Sp (e_p ,t) value must be decreased, meaning that its time derivative should be negative $\dot{}$Sp (e_p ,t). Similarly, if Sp (e_p ,t) < 0, then $\dot{}$Sp (e_p ,t) > 0 According to (12) and (14), the criteria to choose the matrix vector should be

1. If $S_P(e_P, t) > 0 \Rightarrow \dot{S}_P(e_P, t) < 0 \Rightarrow P < P_{\text{ref}}$, then choose a vector suitable to increase P.
2. If $S_P(e_P, t) < 0 \Rightarrow \dot{S}_P(e_P, t) > 0 \Rightarrow P > P_{\text{ref}}$, 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. (16)

The same procedure should be applied to the reactive power error. To choose a vector, from (4) and (12), and considering Pref and V_d in steady state, the following can be written:

$$\dot{S}_P(e_P, t) = k_P\left(\frac{\mathrm{d}P_{\text{ref}}}{\mathrm{d}t} - \frac{dP}{\mathrm{d}t}\right) = -k_P\frac{\mathrm{d}P}{\mathrm{d}t} = -k_P\frac{d(V_d I_d)}{\mathrm{d}t} = -k_P V_d\frac{dI_d}{\mathrm{d}t}. \quad (17)$$

From (16), considering V_d and Pref constant, if Sp (e_p ,t) > 0 , then it must be $\dot{S}$p (e_p ,t) < 0. From (17), if Kp V_d is positive, then $dI_d/dt > 0$, meaning that P must increase. From the equivalent model in dq coordinates presented in (1),if the chosen vector has $V_{Ld} > V_{R0d - \omega L2Id+} R_2 I_d$, then $dI_d/dt > 0$, the selected vector being suitable to increase the active power (reaching condition). Similarly, from (5) and (13), with reactive power Qref and V_d in steady state

$$\dot{S}_Q(e_Q, t) = k_Q\left(\frac{dQ_{\text{ref}}}{\mathrm{d}t} - \frac{dQ}{\mathrm{d}t}\right) = -k_Q\frac{\mathrm{dQ}}{\mathrm{d}t} = -k_Q\frac{d(-V_d I_q)}{\mathrm{d}t} = k_Q V_d\frac{\mathrm{d}I_q}{\mathrm{d}t}. \quad (18)$$

Considering the Iq current dynamics written in dq coordinates (2) then, to ensure the reaching condition, the chosen vector must have $V_{Lq} < V_{R0q + \omega L2Id+} R_2 I_q$, to guarantee then $dI_d/dt < 0$, meaning the voltage vector has a q component suitable to increase the reactive power. To ease vector selection (Table I), sliding surfaces and should be transformed to coordinates. To design the DPC control system, the six vectors of group I will not be used, since they require extra algorithms to calculate their time-varying phase. From group II, the variable amplitude vectors, only the 12 highest amplitude voltage vectors are certain to be able to guarantee the previously discussed required levels of V_{Ld} and V_{Lq} needed to fulfill the reaching conditions. The lowest amplitude voltages vectors, or the three null vectors of group III, could be used for near zero errors. If the control errors e_p and e_Q are quantized using two hysteresis comparators, each with three levels (-1, 0 and +1), 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 Cα= Sα (ep ,t) > 0 and $C_\beta = S_\beta$ (e_p ,t) > 0. Thendp/dt > 0 and dQ/dt< 0, $dI_\alpha/dt > 0$ imply that $dI_\beta/dt > 0$ 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 vector to be applied should be +9 or -7. The final choice between these two depends on the matrix reactive power controller result C_{Qi}. 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.

TABLE II
STATE-SPACE VECTORS SELECTION FOR DIFFERENT ERROR COMBINATIONS

C_α	C_β	Sector					
		V_i 12; 1	V_i 2; 3	V_i 4; 5	V_i 6; 7	V_i 8; 9	V_i 10; 11
-1	+1	-9; +7	-9; +8	+8; -7	-7; +9	+9; -8	-8; +7
-1	0	+3; -1	+3; -2	-2; +1	+1; -3	-3; +2	+2; -1
-1	-1	-6; +4	-6; +5	+5; -4	-4; +6	+6; -5	-5; +4
0	+1	-9; +7; +6; -4	-9; +8; +6; -5	+8; -7; -5; +4	-7; +9; +4; -6	+9; -8; -6; +5	-8; +7; +5; -4
0	0	Za; Zb; Zc; -8;+2;-5;+8;-2;+5	Za; Zb; Zc; -7;+1;-4; +7;-1;+4	Za; Zb; Zc; +9;-3;+6;-9;+3;-6	Za; Zb; Zc; -8;+2;-5;+8;-2;+5	Za; Zb; Zc; -7;+1;-4; +7;-1;+4	Za; Zb; Zc; -9;+3;-6; +9;-3;+6
0	-1	-6; +4; +9; -7	+5; -6; -8; +9	+5; -4; -8; +7	-4; +6; +7; -9	+6; -5; -9; +8	-5; +4; +8; -7
+1	+1	+6; -4	+6; -5	-5; +4	+4; -6	-6; +5	+5; -4
+1	0	-3; +1	+2; -3	-1; +2	+3; -1	-2; +3	+1; -2
+1	-1	+9; -7	+9; -8	+7; -8	+7; -9	-9; +8	+8; -7

3. Direct Power Control Using Space Vector Modulation of Mc

The SVM technique, used for most three-phase converters, is based on the representation of output voltages or input currents resulting from all allowable matrix converter switching combinations, as vectors in the complex plane. It has the advantage of allowing a better selection of the required voltage and current vectors, simplifying control algorithms and providing maximum voltage transfer ratio without the need to add third harmonic modulator components [7]. Based on sliding surfaces, the state-space vectors have to be chosen in order to verify the stability conditions. Accordingly, the sliding mode is reached only when the vectors applied to the converter have the necessary amplitude and direction. The matrix converter output voltage and input current vectors (Table 1) have the following characteristics. The vectors of group I have high fixed amplitude and should be able to guarantee the stability condition. However, as they rotate in the αβ-plane, they may not have the correct direction when necessary (there are only six vectors). Besides, they are not easy to locate, as it will be necessary to consider at least 12 sectors for the mains voltages (Fig. 4), in order to know their approximate location. The 18 vectors of group II have variable amplitude and may not always guarantee the stability condition for this reason, at each time instant, only the 12 highest amplitude voltage vectors, which must be able to guarantee the stability condition, should be chosen to control the output variables.

The null vectors of group III guarantee the stability condition when both sliding surface values are nearly zero. As a result in order to simplify the control system, the six vectors of group I will not be used. The choice of the remaining 15 voltage vectors, the 12 highest amplitude vectors of group II and the three null vectors of group III, will guarantee the matrix converter maximum input/output voltage transfer ratio of 0.866 like in SVM [7].

The MC adopts a Space Vector Modulation (SVM) switching strategy [6] which can be used for any MC applications. The SVM switching approach enables the MC to:

• Achieve the maximum voltage transfer ratio without utilizing the third harmonic component injection method;
• Accommodate any input power factor independent of the output power factor;
• Reduce the effective switching frequency in each cycle, and thus the switching losses;
• Minimize harmonics.

In an SVM strategy only the switching states of Group II and III are utilized. The switching states in Group I are not used since the corresponding SSVs are rotating with time. Output voltage SSVs and input current SSVs of each switching state in Group II are illustrated in Fig.6. and Fig.7. The output voltage (input current) SSVs are expressed in the output (input) αβ plane. Sector numbers 1 to 6 are assigned for the vector spaces between two adjacent SSVs in both the input and the output αβ planes as shown below Fig 6. and Fig 7. And corresponding selection of switching states shown in Table IV Therefore, each switching state specifies one output voltage and one input current space vector, which are called as voltage and current switching space vectors (SSVs), respectively.

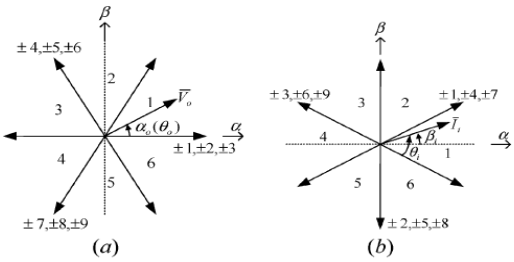

Fig. 6: (a) Output voltage SSVs. (b) Input current SSVs.

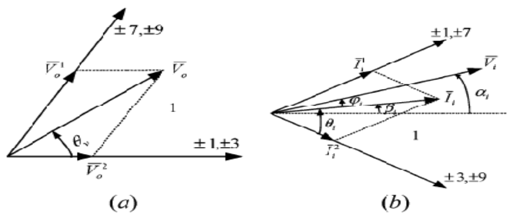

Fig. 7: (a) Output voltage vector synthesis. (b) Input current vector synthesis

TABLE IV
SELECTION OF SWITCHING STATES

Sector # of $\bar{I}_i$	Sector # of V_o											
	1 or 4				2 or 5				3 or 6			
1 or 4	7	9	1	3	4	6	7	9	1	3	4	6
2 or 5	8	7	2	1	5	4	8	7	2	1	5	4
3 or 6	9	8	3	2	6	5	9	8	3	2	6	5
Symbol	I	II	III	IV	I	II	III	IV	I	II	III	IV

4. 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. 4.3) dynamics (6) has a strong relative degree of two, and then a suitable sliding surface (19) will be a linear combination of the desired reactive power error and its first-order time derivative

$$S_{Q_i}(e_{Q_i},t) = (Q_{i_{\text{ref}}} - Q_i) + K_{Q_i}\frac{d}{dt}(Q_{i_{\text{ref}}} - Q_i). \quad (19)$$

The time derivative can be approximated by a discrete time difference, as has been chosen to obtain a suitable switching frequency, since as stated before, this sliding surface needs to be quantized only in two levels (-1 and +1) using one hysteresis comparator. To fulfill a stability condition similar to (15), considering the input filter dynamics (6), (20) is obtained

$$\begin{aligned}
&\dot{S}_{Qi}(e_{Qi},t) = \\
&V_{id}\left(\frac{\mathrm{d}i_{iq}}{\mathrm{d}t} + K_{Qi}\frac{\mathrm{d}^2 i_{iq}}{\mathrm{d}t^2}\right) = V_{id}\left(-\omega i_{id} + \frac{1}{2\sqrt{3}l}V_d - \frac{1}{2l}V_q\right) + \\
&V_{id}K_{Qi}\left(-\omega^2 i_{iq} + \frac{\omega}{l}V_d + \frac{\omega}{\sqrt{3}l}V_q - \frac{\omega}{l}V_{id} - \frac{i_{iq}}{3lC} + \frac{i_q}{3lC}\right).
\end{aligned} \quad (20)$$

From (20), it is seen that the control input, the iq matrix input current, must have enough amplitude to impose the sign of $\dot{S}_{Qi}$ (e_Qi,t). Supposing that there is enough iq amplitude, (19) and (20) are used to establish the criteria (21) to choose the adequate matrix input current vector that imposes the needed
sign of the matrix input-phase current iq related to the output-phase currents by (9).

1. If $S_{Q_i}(e_{Q_i},t) > 0 \Rightarrow \dot{S}_{Q_i}(e_{Q_i},t) < 0$, then select vector with current $i_q < 0$ to increase Q_i
2. If $S_{Q_i}(e_{Q_i},t) < 0 \Rightarrow \dot{S}_{Q_i}(e_{Q_i},t) > 0$, then select vector with current $i_q > 0$ to decrease Q_i. (21)

If then select vector with current to increase If then select vector with current to decrease (21) The sliding mode is reached when vectors applied to the converter have the necessary current amplitude to satisfy stability conditions, such as (15). Therefore, to choose the most adequate vector in the chosen dq 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 dq –axis location is synchronous with the input voltage (i.e. dq 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. Considering the previous example, with the input voltage at sector V_{i1} and sliding surfaces signals Sα (e_P,t) > 0and S_β (eQ,t) < 0 both vectors +9 or -7 would be suitable to control the line active and reactive powers errors (Fig. 4.4). However, these vectors have a different effect on the $\dot{S}_Q$ (eQ,t) value: if iq has a suitable amplitude, vector +9 leads to $\dot{S}_Q$ (eQ,t) > 0 while vector -7 originates $\dot{S}_{Qi}$ (eQ,t) < 0. So, vector should be chosen if the input reactive power sliding surface is quantized as C_{Qi} = -1, while vector -7 should be chosen when is quantized as C_{Qi}= + 1. When the active and reactive power errors are quantized as zero, Sα (e_P,t) =0 and S_β (e_Q,t) = 0, the null vectors of group III, or the lowest amplitude voltages vectors at sector V_{i1} (-8,+2,-5,+8,-2,+5) at Fig. 4.(b) could be used. These vectors do not produce significant effects on the line active and reactive power values, but the lowest amplitude voltage vectors have a high influence on the control of matrix reactive power. Using the same reasoning for the remaining eight combinations at sector V_{i1} and applying it for the other output current sectors, Table III is obtained.

IV. IMPLEMENTATION OF THE DPC-MC AS UPFC

Control scheme of direct power control of the three-phase matrix converter operating as a UPFC. As shown in the block diagrams [Fig. 8] 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 q 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, using tables derived from Tables II and III for all voltage sectors.

TABLE III
STATE-SPACE VECTORS SELECTION, FOR INPUT VOLTAGES LOCATED AT SECTOR V_i1

C_α	C_β	Sector: $I_0 12$; $I_0 1$ (C_{Qi})		$I_0 2$; $I_0 3$ (C_{Qi})		$I_0 4$; $I_0 5$ (C_{Qi})		$I_0 6$; $I_0 7$ (C_{Qi})		$I_0 8$; $I_0 9$ (C_{Qi})		$I_0 10$; $I_0 11$ (C_{Qi})	
		+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
-1	+1	-9	+7	-9	+7	-9	+7	+7	-9	+7	-9	+7	-9
-1	0	+3	-1	+3	-1	-1	+3	-1	+3	-1	+3	+3	-1
-1	-1	-6	+4	+4	-6	+4	-6	+4	-6	-6	+4	-6	+4
0	+1	-9	+7	-9	+7	-9	+7	+7	-9	+7	-9	+7	-9
0	0	-2	+2	+8	-8	-5	+5	+2	-2	-8	+8	+5	-5
0	-1	-7	+9	-7	+9	-7	+9	+9	-7	+9	-7	+9	-7
+1	+1	-4	+6	+6	-4	+6	-4	+6	-4	-4	+6	-4	+6
+1	0	+1	-3	+1	-3	-3	+1	-3	+1	-3	+1	+1	-3
+1	-1	-7	+9	-7	+9	-7	+9	+9	-7	+9	-7	+9	-7

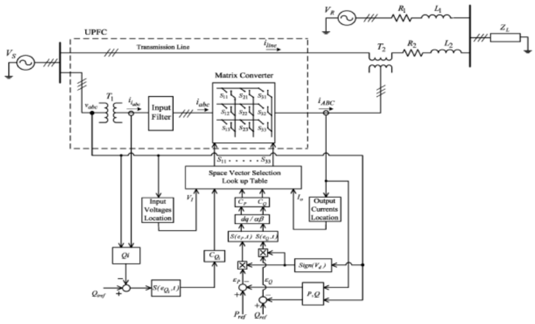

Fig 8: Control scheme of direct power control of the Three-phase matrix converter operating as a UPFC

V. SIMULATION RESULTS

The performance of the proposed direct control system was evaluated with a detailed simulation model in Fig.9, and matrix converter in Fig.10 using the MATLAB/Simulink SimPowerSystems to represent the matrix converter transformers, sources and transmission lines, and Simulink blocks to simulate the control system. Ideal switches were considered to simulate matrix converter semiconductors minimizing simulation times. In order to evaluate the performance of the direct controlled system, some tests were done, under different operating conditions, and the simulation results in Fig.11-Fig.14, obtained using the proposed method, were compared with the well-known Venturing and SVM strategies .The Matrix converter output currents (iA, iB, iC) THD for DPC and FUZZY shown in Fig.15.The controlled matrix converter should be able to guarantee that the output variables follow their references and, at the same time, that the input currents have the desired power factor: unity power factor if the matrix converter is used to control AC drives; and unity or leading/lagging power factor if the converter is used in applications related to power quality enhancement.

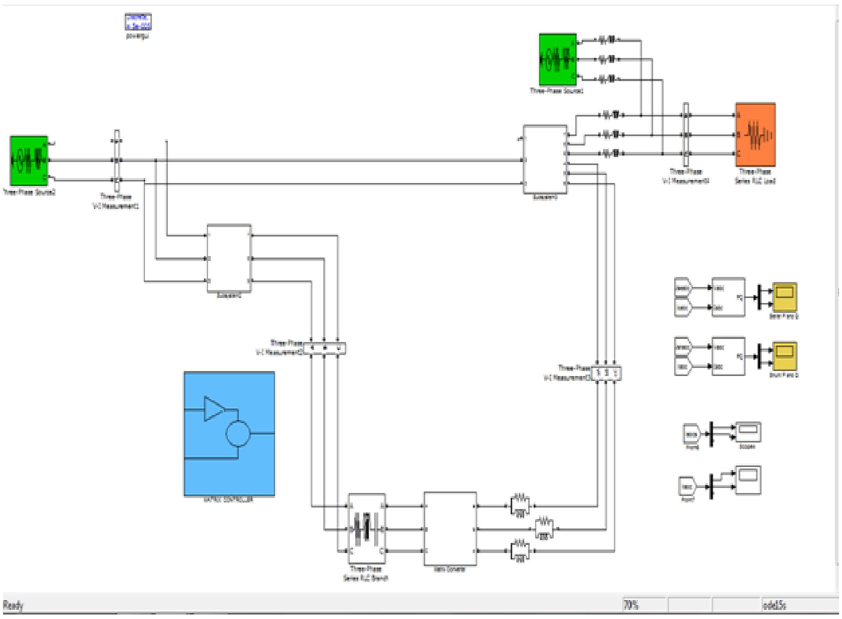

Fig 9: Simulation Model of UPFC with Matrix Converter

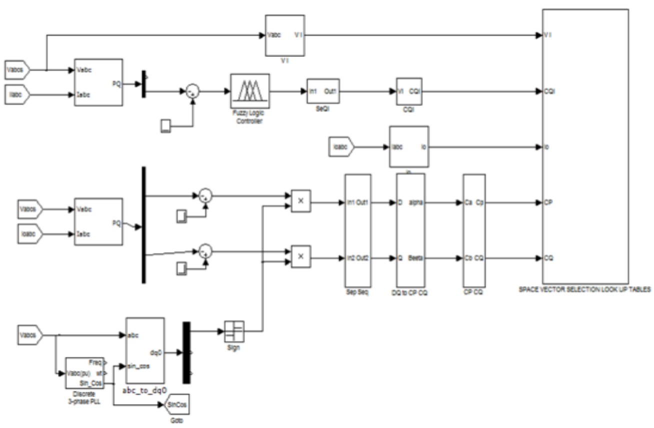

Fig 10: Fuzzy based DPC matrix converter control scheme.

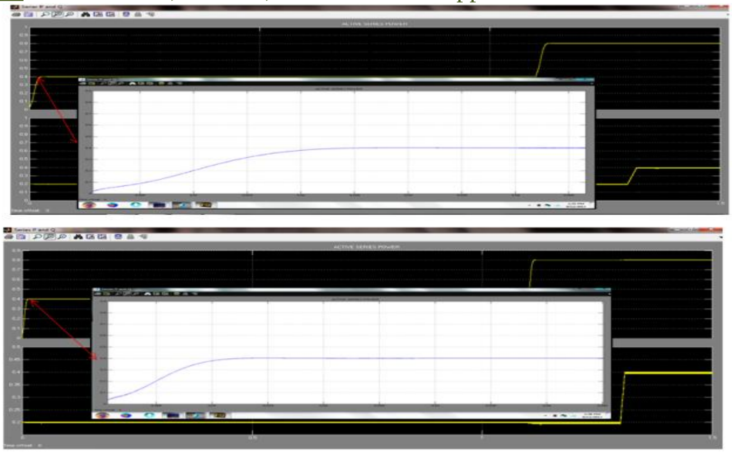

Fig 11: Simulation Result of Active and Reactive Series Power Responses with DPC and Fuzzy

Fig 12: Simulation result of Active and Reactive shunt power with DPC

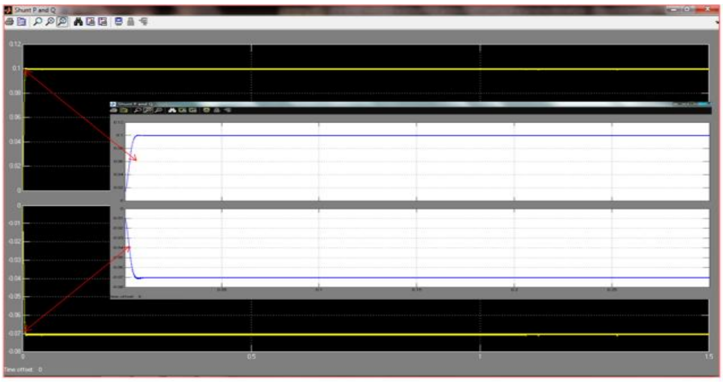

Fig 13: Simulation results of Active and Reactive shunt power with fuzzy

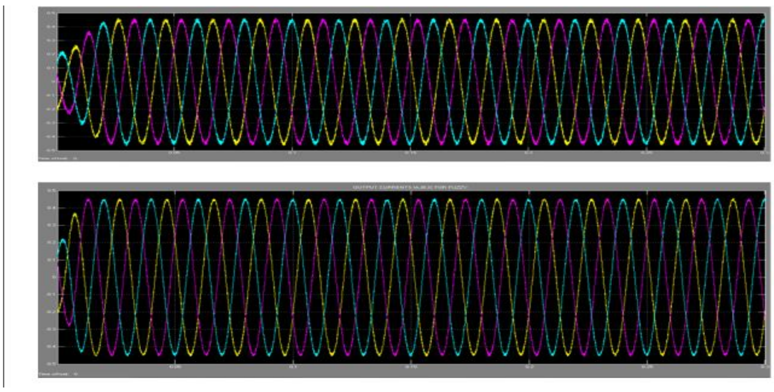

Fig 14 : Matrix converter output currents (iA, iB, iC) for DPC and FUZZY

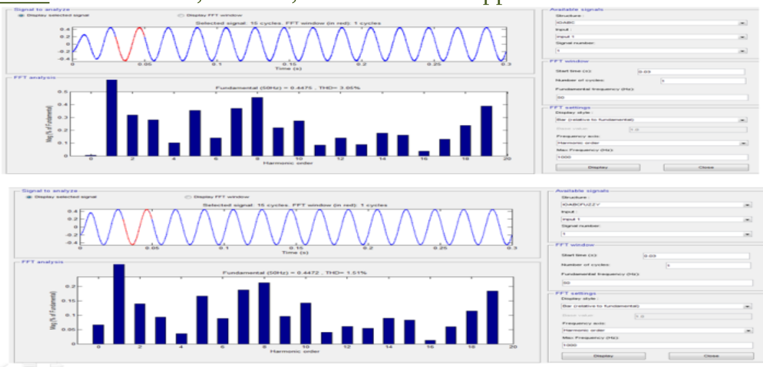

Fig. 15 : Matrix converter output currents (iA, iB, iC) THD for DPC and FUZZY

VI. CONCLUSION

The use of sliding mode controllers in variable structure systems such as matrix converters may present advantages such as easy on-line implementation and a quick and efficient choice of the correct switching combinations, ensuring that the system tracks their references. The active and reactive power flow can be advantageously controlled by using the proposed Fuzzy based DPC. The Fuzzy based DPC give Fast response times. It ensures transmission-line power control as well as sending end reactive power or power factor control. The dynamic and steady-state behavior of the proposed fuzzy based DPC-MC P, Q control method is evaluated and discussed using detailed simulations implementation. Obtained simulation results show that active and reactive power flow can be advantageously controlled by using the proposed fuzzy based DPC. The results of line and input matrix converter Currents are almost sinusoidal with small ripple content. From 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 responses. The fuzzy controller forces the amplitude of the output current space vector to be constant so that the output current is free of harmonic.

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