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Advanced Direct Power Control of Matrix Converter Based Unified Power-Flow Controller

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ABSTRACT

An electrical power system is a large interconnected network that requires a careful design to maintain the system with continuous power flow operation without any limitations. Flexible Alternating Current Transmission System (FACTS) is an application of a power electronics device to control the power flow and to improve the system stability of a power system. This paper presents 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. 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. Experimental results of DPC controllers for MC-UPFC show decoupled active and reactive power control, zero steady-state tracking error, and fast response times. Compared to an MC-UPFC using active and reactive power linear controllers based on a modified Venturini high-frequency PWM modulator, the experimental results of the advanced DPC-MC guarantee faster responses without overshoot and no steady-state error, presenting no cross-coupling in dynamic and steady-state responses.

***Key Words**: Direct power control (DPC), matrix converter (MC), unified power-flow controller (UPFC).*

INTRODUCTION

The technology of power system utilities around the world has rapidly evolved with considerable changes in the technology along with improvements in power system structures and operation. The ongoing expansions and growth in the technology, demand a more optimal and profitable operation of a power system with respect to generation, transmission and distribution systems. In the present scenario, most of the power systems in the developing countries with large interconnected networks share the generation reserves to increase the reliability of the power system. However, the increasing complexities of large interconnected networks had fluctuations in reliability of power supply, which resulted in system instability, difficult to control the power flow and security problems that resulted large number blackouts in different parts of the world. The reasons behind the above fault sequences may be due to the systematical errors in planning and operation, weak interconnection of the power system, lack of maintenance or due to overload of the network.

In order to overcome these consequences and to provide the desired power flow along with system stability and reliability, installations of new transmission lines are required. However, installation of new transmission lines with the large interconnected power system are limited to some of the factors like economic cost, environment related issues. These complexities in installing new transmission lines in a power system challenges the power engineers to research on the ways to increase the power flow with the existing transmission line without reduction in system stability and security. In this research process, in the late 1980's the Electric Power Research Institute (EPRI) introduced a concept of technology to improve the power flow, improve the system stability and reliability with the existing power systems. This technology of power electronic devices is termed as Flexible Alternating Current Transmission Systems (FACTS) technology. It provides the ability to increase the controllability and to improve the transmission system operation in terms of power flow, stability limits with advanced control technologies in the existing power systems.

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. These minimum energy storage ac/ac converters have the capability to allow independent reactive control on the UPFC shunt and series converter sides, while guaranteeing that the active power exchanged on the UPFC series connection is always supplied/absorbed by the shunt connection. Conventional UPFC controllers do not guarantee robustness.

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. 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

In this paper, a matrix converter- based UPFC is proposed, using a direct power control approach (DPC-MC) based on an MC-UPFC dynamic model. In order to design UPFCs, presenting robust behavior to parameter variations and to disturbances, the proposed DPC-MC control method is based on sliding mode-control techniques, allowing the real-time selection of adequate matrix vectors to control input and output electrical power. Sliding mode-based DPC-MC controllers can guarantee zero steady-state errors and no overshoots, good tracking performance, and fast dynamic responses, while being simpler to implement and requiring less processing power, when compared to proportional-integral (PI) linear controllers obtained from linear active and reactive power models of UPFC using a modified Venturini high-frequency PWM modulator.

The dynamic and steady-state behavior of the proposed DPC-MC P, Q control method is evaluated and discussed using detailed simulations and experimental implementation. Simulation and experimental results obtained with the nonlinear 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 dynamic and steady-state responses.

MODELING OF THE MATRIX CONVERTER UPFC POWER SYSTEM

A. General Architecture

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 4, represented as a series inductance with series resistance (L_2 and R_2), through coupling transformers and T_1 and T_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.

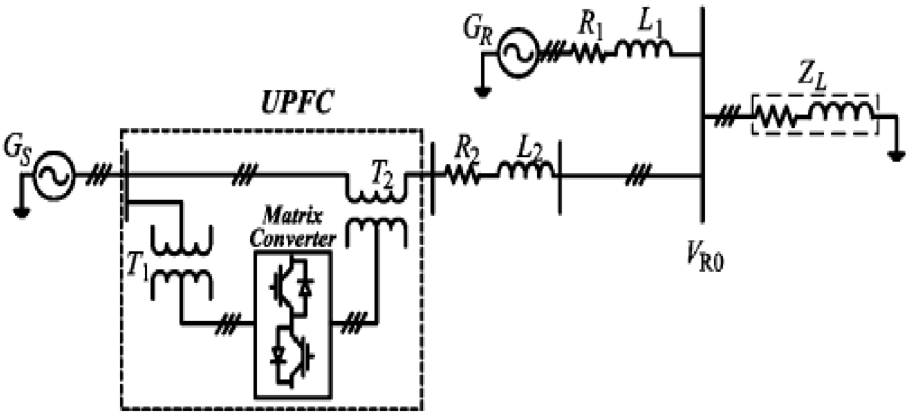


Fig. 1. Transmission network with matrix converter UPFC.

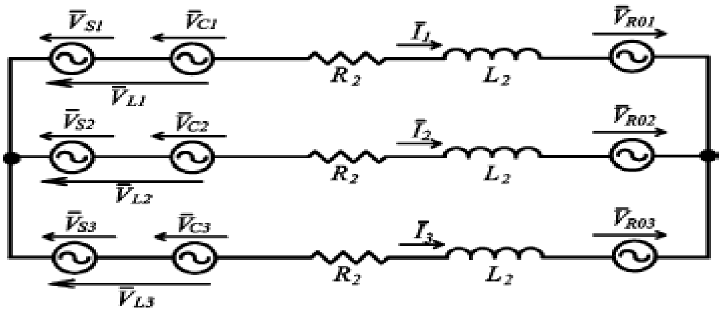


Fig. 2. Three-phase equivalent circuit of the matrix UPFC and transmission line.

A matrix converter is a direct frequency changer. This converter consists of an array of n×m bidirectional switches arranged so that any of the output lines of the converter can be connected to any of the input lines. The bidirectional switch is realized by using some semiconductor devices. They can be either discrete or integrated to the module. The bidirectional switch can be implemented in various ways. For the matrix converter, we chose modules which include 3 bidirectional switches in common emitter a configuration. The modulator is thus realized for these switchers.

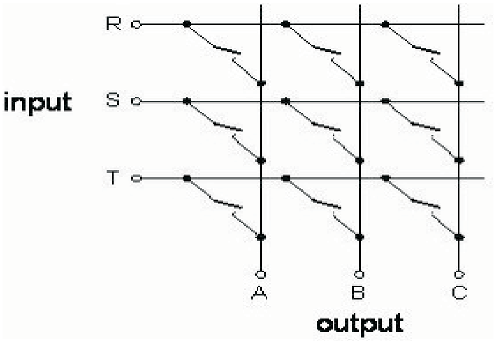


Fig. 3: Matrix converter 3×3

The Matrix Converter is a single stage converter which has an array of m× n bidirectional power switches to connect, directly, an m-phase voltage source to an n-phase load. The Matrix Converter of 3× 3 switches, shown in Figure5, has the highest practical interest because it connects a three-phase voltage source with a three-phase load, typically a motor. Normally, the matrix converter is fed by a voltage source and for this reason, and the input terminals should not be short-circuited.
On the other hand, the load has typically an inductive nature and for this reason an output phase must never be opened. Defining the switching function of a single switch as

$$\text{Skj} = \begin{cases} 1, \text{Switch Skj closed} \\ 0, \text{Switch Skj open} \end{cases} \quad k = \{A\ B\ C\} \quad j = \{a\ b\ c\}$$

The constraints discussed above can be expressed by

$$\text{SAj} + \text{SBj} + \text{SCj} = 1, \quad j = \{a\ b\ c\}$$

With these restrictions, the 3× 3 Matrix Converter has 27 possible switching states.

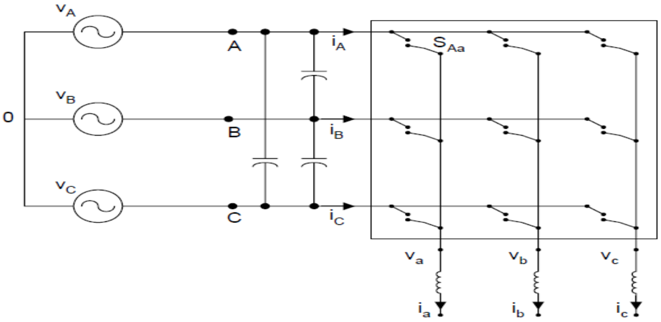


Fig 4: Simplified circuit of a 3× 3 Matrix Converter.

The load and source voltages are referenced to the supply neutral, '0' in the Figure 4, and can be expressed as vectors defined by:

$$V_o = \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix}, \quad V_i = \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix}$$

The relationship between load and input voltages can be expressed as:

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix}$$

$Vo = T \times Vi$

Where *T* is the instantaneous transfer matrix.

In the same form, the following relationships are valid for the input and output currents:

$$i_i = \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad i_o = \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix}$$

$i_i = T^T \cdot io$

Where T_T is the transpose matrix of T.

The above gives the instantaneous relationships between input and output quantities. To derive modulation rules, it is also necessary to consider the switching pattern that is employed. This typically follows a form similar to that shown in the Figure 5.

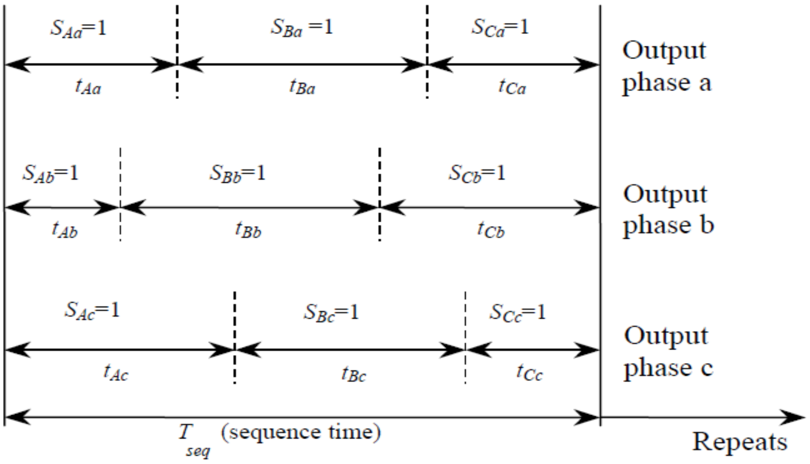


FIGURE 5: General form of switching pattern.

By considering that the bidirectional power switches work with high switching frequency, a low frequency output voltage of variable amplitude and frequency can be generated by modulating the duty cycle of the switches using their respective switching functions. Let $M_{kj}(t)$ be the duty cycle of switch $S_{kj}(t)$, defined as $M_{kj}(t) = t_{kj}/T_{seq}$, which can have the following values:

$0 < Mkj(t) < 1, \quad k = \{A\ B\ C\}, \quad j = \{a\ b\ c\}$

The low-frequency transfer matrix is defined by

$$M(t) = \begin{bmatrix} M_{Aa} & M_{Ba} & M_{Ca} \\ M_{Ab} & M_{Bb} & M_{Cb} \\ M_{Ac} & M_{Bc} & M_{Cc} \end{bmatrix}$$

The low-frequency component of the output phase voltage is given by

$Vo(t) = M(t) \cdot Vi(t)$

The low-frequency component of the input current is

$i_i(t) = M(t)^T \cdot io(t)$

The Matrix Converter is a forced commutated converter which uses an array of controlled bidirectional switches as the main power elements to create a variable output voltage system with unrestricted frequency. It does not have any dc-link circuit and does not need any large energy storage elements. The matrix converter is an array of bidirectional switches as the main power elements, which interconnects directly the power supply to the load, without using any dc-link or large energy storage elements.

The most important characteristics of matrix converters are; 1) Simple and compact power circuit, 2) Generation of load voltage with arbitrary amplitude and frequency, 3) Sinusoidal input and output currents, 4) Operation with unity power factor, 5) Regeneration capability.

These highly attractive characteristics are the reason for the tremendous interest in this topology. The key element in a matrix converter is the fully controlled four quadrant bidirectional switch, which allows high frequency operation. The early work dedicated to unrestricted frequency changers used thyristors with external forced commutation circuits to implement the bi-directional controlled switch. With this solution the power circuit was bulky and the performance was poor. The introduction of power transistors for implementing the bidirectional switches made the matrix converter topology more attractive. However, the real development of matrix converters starts with the work of Venturini and Alesina published in 1980.

They presented the power circuit of the converter as a matrix of bi-directional power switches and they introduced the name “Matrix Converter.” One of their main contributions is the development of a rigorous mathematical analysis to describe the low-frequency behavior of the converter, introducing the “low frequency modulation matrix” concept. In their modulation method, also known as the direct transfer function approach, the output voltages are obtained by the multiplication of the modulation (also called transfer) matrix with the input voltages.

DIRECT POWER CONTROL OF MC-UPFC

Line Active and Reactive Power Sliding Surfaces

The DPC controllers for line power flow are here derived based on the sliding mode control theory. In steady state, V_d is imposed by source Vs. 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}, Q_{ref} and the actual transmitted powers P, Q, respectively.

$$e_P = P_{\mathrm{ref}} - P$$
$$e_Q = Q_{\mathrm{ref}} - Q.$$

Then, the 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.

$$S_P(e_P,t) = k_P(P_{\mathrm{ref}} - P) = 0$$
$$S_Q(e_Q,t) = k_Q(Q_{\mathrm{ref}} - Q) = 0.$$

The proportional gains K_p and K_q are chosen to impose appropriate switching frequencies.

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 must be verified

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

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

To design the DPC control system, the six vectors will not be used, since they require extra algorithms to calculate their time-varying phase. 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 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 (9x2=18) 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. 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.

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_{Qi} (e_{qi},t) will be a linear combination of the desired reactive power error $e_{qi}=Q_{iref}-Q_i$ and its first-order time derivative.

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

The time derivative can be approximated by a discrete time difference, as K_{Qi} 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 considering the input filter dynamics is obtained.

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 G_S voltages and output currents necessary to calculate $S_\alpha(e_p,t)$ and $S_\beta(e_Q,t)$ 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 I and II for all voltage sectors. 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.

Voltage Control in d-q Reference Frame

The output voltages are measured across the capacitors in the output filter and are then feedback separately to the system control. In the d-q reference frame the three- phase output voltages are transformed into two dc signals on the d and q axis.

Using the designed tracking controller on each of the two axes, the presence of the interpreter will ensure a small steady state error on the voltage loop. The control signal in d-q frame are converted back to the ABC reference frame an applied to the modulator. These signal are the reference signal required by the modulator in order to produce the pulses needed to commutate the bi-directional switches. Figure 7 shows the control strategy in d-q reference frame.

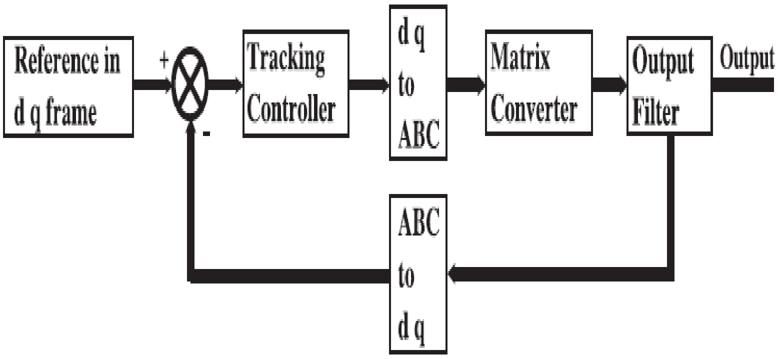


Figure 7: Control strategy in d-q reference frame.

Voltage Control in ABC Reference Frame

The problem presented in previous section when the Matrix Converter is connected to an unbalanced load can be solved using a control system working directly in the ABC reference frame. The reference signals which are a set of a three-phase rms voltages at 400Hz in the ABC frame are compared to the voltages measured across the output filter capacitors. The error signal obtained is then applied to the tracking controller on each phase. Each tracking controller generates a control signal which is applied directly to the modulator. Then the modulator produces the pulses required to commutate the bi-directional switches. The general scheme of the system used is shown in Figure 8. The procedure used to design the tracking controller of for the ABC reference is the same as the one used in the design of the tracking controller in the d-q reference frame. In this case because the gain is now set as 0.6. Since the reference of our control is a 400Hz three-phase signal, the interpreter present in the controller will not be able to achieve a small steady state error, being the all closed-loop system of a limited bandwidth. Therefore a gain has been introduced in order to compensate for the amplitude mismatch in the output. The value of this gain has been found to be 6 by trial and error. When the control system was design, the block representing the Matrix Converter was considered as a unity gain. In the practical implementation, the Matrix Converter consists of electronic components which have voltage drops and dissipate energy and therefore the Matrix Converter has a transfer function different from a unity gain. This modifies the closed loop considered in the design of the tracking controller. In the design of the controller, only the output filter has been considered as the plant. The Matrix Converter block is not considered as part of the closed loop. In practice, it have been found that the Matrix Converter can be replaced by a gain with a value between 5 and 6. Also, the block representing the Matrix Converter introduces a delay. This delay can be compensated by the controller.

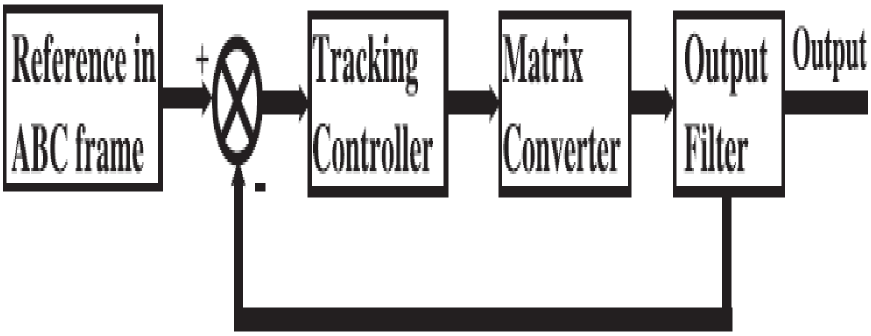


Figure 8: Control strategy in ABC reference frame.

TABLE I: STATE-SPACE VECTORS SELECTION, FOR INPUT VOLTAGES LOCATED AT SECTOR V_i 1

C_α	C_β	***Sector***											
		$I_0 12 ; I_0 1$		$I_0 2 ; I_0 3$		$I_0 4 ; I_0 5$		$I_0 6 ; I_0 7$		$I_0 8 ; I_0 9$		$I_0 10; I_0 11$	
		C_{Qi}		C_{Qi}		C_{Qi}		C_{Qi}		C_{Qi}		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

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

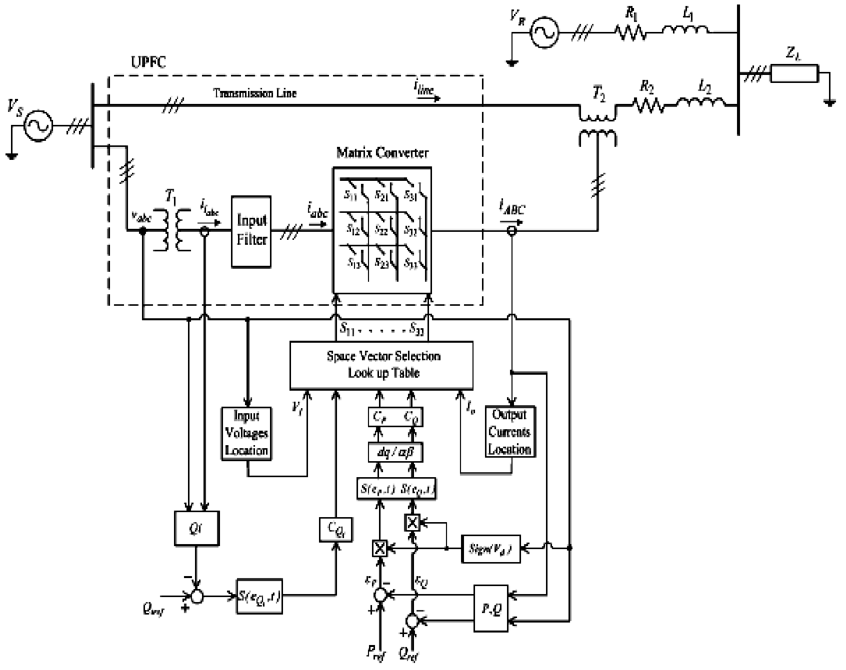
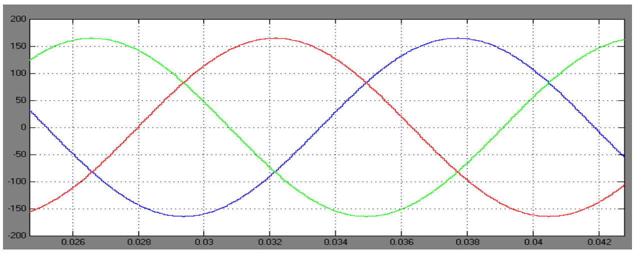


Fig.6. Control scheme of direct power control of the three-phase matrix converter operating as a UPFC.

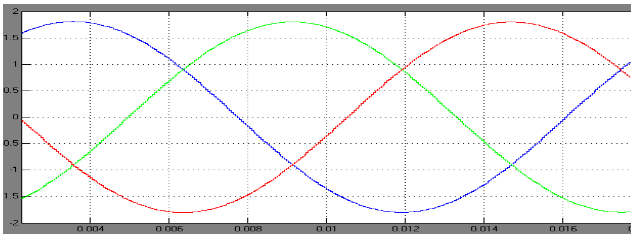
SIMULATION RESULTS

The performance of the proposed direct control system was evaluated with a detailed simulation model 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.

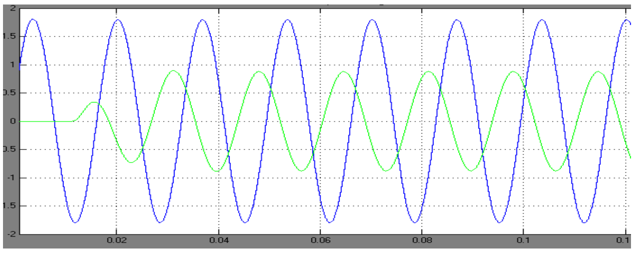
Input voltage:-



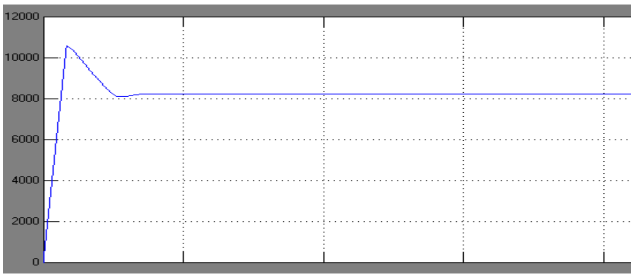
Input current:-



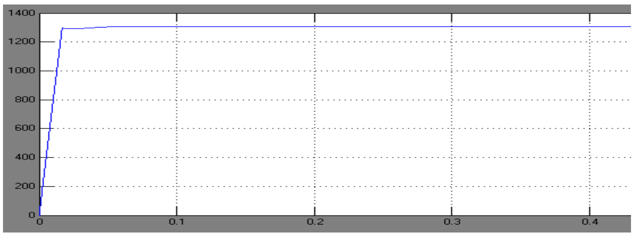
Injected voltage and current:-



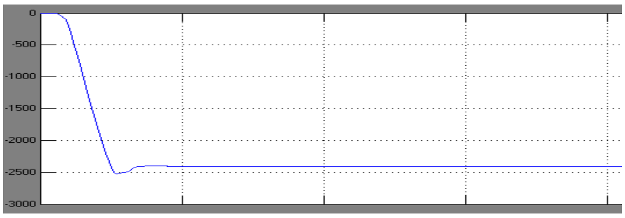
Line active power:-



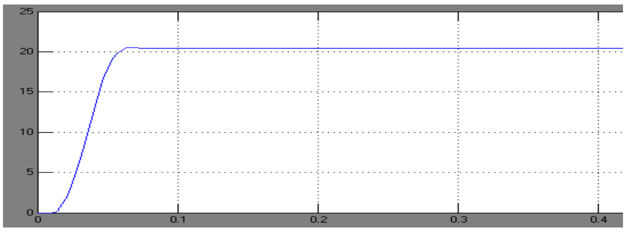
Line reactive power:-



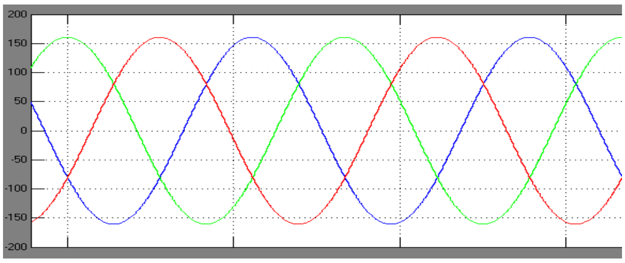
Injected line reactive power:-



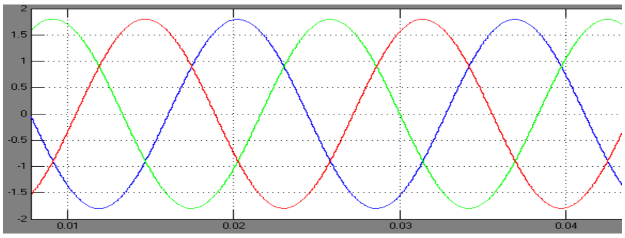
Injected line active power:-



Output voltage:-



Output current:-



CONCLUSION

This paper derived advanced nonlinear direct power controllers, based on sliding mode control techniques, for matrix converters connected to power transmission lines as UPFCs. Presented simulation 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 nonmodeled dynamics and fast response times, thus confirming the expected performance of the presented nonlinear DPC methodology. The obtained DPC-MC results were compared to PI linear active and reactive power controllers using a modified Venturini high-frequency PWM modulator. Despite showing a suitable dynamic response, the PI performance is inferior when compared to DPC. Furthermore, the PI controllers and modulator take longer times to compute. Obtained results show that DPC is a strong nonlinear control candidate for line active and reactive power flow. It ensures transmission-line power control as well as sending end reactive power or power factor control.

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