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A Novel Three Phase Dual-Input Dual-Output Indirect Matrix Converter by Model Predictive Controller

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Abstract: -- **This paper presents a novel Matrix converter two AC input and two ac outputs. The presented topology is based on the traditional indirect matrix converter (IMC) but with its rear and front end six switch converter is replaced by a compact nine switch rectifier, inverter with only three extra switches added. The proposed converter can produce two sets of three phase ac outputs. This Indirect matrix converter topology can independently supply ac power from two different three phase ac power sources. A model predictive control (MPC) uses the discrete time model of the converter and load parameters are used to predict the behavior of the input reactive power on the supply side and the output currents for each valid switching state the control method selects the best commutation state. The control action which minimizes the cost function is selected and applied to the system for the next time interval. This paper presents a finite control set of model predictive control strategy for a dual input- dual output indirect matrix converter.**

Index Terms: — **Matrix converter nine-switch converter, dual input sources, dual output loads, Model predictive controller.**

I. INTRODUCTION

Over the last few years, research on indirect matrix converters has benefited from advances in semiconductor technologies, which have mainly contributed toward enhancing efficiency. Compared with the standard matrix converter, this topology can use a simpler modulation [1] scheme and does not need an additional overvoltage protection system. Conversely, the current path from input to output produces higher power losses. This can be partly mitigated by the use of semiconductors such as reverse blocking insulated-gate bipolar transistors (RB-IGBTs), which have already been used in conventional matrix converters [2]. Additionally, some studies have focused on sparse matrix topologies, which can improve power density by reducing the number of semiconductors at the expense of functionality. This is the case of the sparse matrix, the very sparse matrix, and the ultra sparse matrix converter, which feature 15, 12, and 9 switches, respectively [12].

The three-phase to three-phase ac/ac matrix converters Matrix converters allow direct ac/ac power conversion without the dc energy storage component. They have recently received considerable attention as an alternative to the conventional ac/ac converter, which is composed of rectifier/dc-link capacitor/inverter structures. MCs have many advantages such as sinusoidal input and output current waveforms, unity power factor at the input side and

Increased power density. In addition, MCs are highly reliable and durable due to the lack of a dc-link electrolytic capacitor for energy storage.

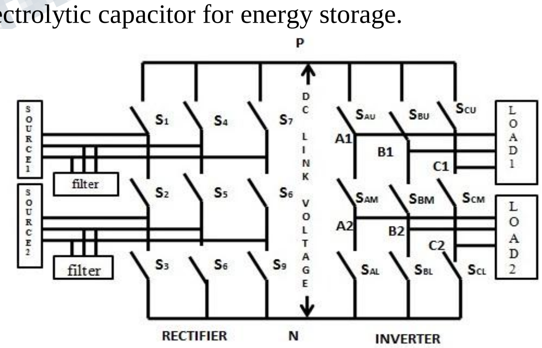

Fig. 1.Dual input Dual output indirect matrix converter

MCs are classified into two types: direct matrix converters (DMC) and indirect matrix converters (IMC). The DMC is a one stage ac/ac direct converter, where three-phase input voltages are directly connected to three-phase output loads through nine bidirectional switches On the other hand, the IMC topology is based on the ac/dc/ac power conversion with no intermediate capacitor[16]-[17]. The IMC comprises two stages such

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as rectifier stage and inverter stage. DMC and IMC provide the same input/output performance, maximum voltage transfer ratio, and number of power switches. However, the IMC topology provides a soft switching commutation that is not applicable in DMC. Furthermore, the IMC needs the simpler clamp circuit for overvoltage protection as compared to the DMC.

On the other hand, Integration of two AC sources into the load it requires the development of the corresponding power electronics technologies with the high efficiency and low cost. Matrix converters feature several advantages compared with standard two-level converters, such as a bidirectional power flow and the reduced size of the reactive components. Different kinds of converters without dc link have been presented in the technical literature. The IMC with dual three-phase inputs and outputs is also introduced in order to reduce the total cost and system volume. Dual ac-drive systems from conventional voltage source inverter (VSI) have been studied for special industrial applications such as electric vehicles, railway traction system, steel processing, textile manufacturing, and winders. However, they have the same drawbacks associated with the rectifier/dc-link capacitor /inverter conversion system. Dual three-phase outputs IMC topology consists of an two input stage and two output stages with a nine number of switches for each converter, as shown in Fig. 1.This topology is based on the traditional IMC, but the 12 switches is replaced by a nine-switch converter as shown in Fig. 1. Even if this topology works with reduced numbers of power switches, the switch capacity in the nine-switch converter stage is doubled.

The conventional solution for integrating ac/ac energy conversion systems into the load with a separate converter for each power source. The advantages of building a separate converter for a power source are easy control and design. However, the identical topology of converters and sequential operation of the switches may introduce hardware redundancy, which leads to all lower switch usability. Therefore, it is possible to integrate two conversion systems into one compact converter to reduce the number of switches. The converter size is mainly determined by the volume of passive components like inductors and capacitors. Both the conventional solution and the compact system [13] need a large size dc electrolytic capacitor to formulate two stages energy conversions to the load. This electrolytic capacitor may cause premature failure and increase the size of the converter. Furthermore, a dc-link voltage sensor is required for the decoupled control of the input ac/dc converter and output dc/ac inverter.

To prolong the lifetime of converter, foil capacitor instead of electrolytic capacitor was used for back-to-back ac/dc/ac converter [14]. Another alternative solution is matrix converter, which has attracted attention of many researchers for direct ac/ac conversion due to the absence of passive components in the dc-link [15]. An indirect matrix converter (IMC), which consists of rectifier/inverter with a fictitious dc-link, is proposed to replace a conventional matrix converter. The front end and rear end converter in the IMC are switched coordinately to achieve sinusoidal input/output currents. The main drawback of a matrix converter is the limited gain of 0.866 for input –to-output voltage transfer and the complicated commutation issues. However, an ac/ac converter only needs a voltage boost function in some applications. For example, the generator output voltage is always lower than the load voltage in the system. Therefore, the input ac sources can be connected to the voltage source side rather than the load side of an IMC to achieve voltage boost function without additional passive components or step-up transformer.

To remove the dc-link electrolytic capacitor and provide more ac input terminals with reduced switches, this paper proposes a novel dual input dual output matrix converter (DIMC-DOMC) to integrate two ac energy resources into the dual output loads. The six-switch voltage source converter of the IMC is replaced by a nine-switch topology to provide two there phase ac inputs. The modulation schemes for the DIMC are proposed to produce sinusoidal inputs/output current waveforms. Afterwards, detailed control algorithms of the converter with voltage boost function are developed. Commanded currents can be extracted from two input ac sources using the proposed control algorithms. In addition to guaranteeing unity power factors. The simulation results are provided to validate the converter's topology.

Topology description and modulation for the matrix converter

Topology of the DIMC

Conventionally two voltage source rectifiers are normally used to integrate two ac sources into the dual output load to a common inverter with back-to-back ac/dc/ac configuration as show in fig.1. Actually twenty four switches are required and an electrolytic capacitor is connected at the dc-link. Where a bidirectional voltage

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source converter is on the mains side with nine-switch inverters connected to the common fictitious dc-link. In the proposed DIMC, a nine-switch switch converter and a inverter are connected together by a fictitious dc-link as shown in fig .1

The Nine switch converter performs the same function as two voltage source converter (VSCs) which share three common switches (ST_2,ST_5, ST_8). The twelve switches are needed for integration of two ac sources to the two loads. A clamp circuit inclusive of a fast recovery diode in series with a well designed small six foil capacitor should be connected to the fictitious dc-link. This clamp circuit can reduce the dc-link voltage spike and also can absorb the magnetic energy stored in the source-side inductors when the converter is turned off during fault. In normal operation, the diode is reversely biased since the clamp capacitor voltage is higher than the fictitious dc-link voltage.

It can be observed that from the nine-switch topology that the middle switch ST_2 in the first leg is shared by upper and lower converters, and the lower modulation reference v_{rR} is always set lower than the upper reference v_{rA} [16]-[17]. The proposed DIMC can boost the input voltages to a higher level by connecting the voltage source terminals reversely, which allows the input sources with low voltage to be connected to the load at relatively at higher voltages. The summation of modulation indices of the two input converters must be less than or equal to 1 when the frequencies of the two sources are different.

In comparison with the conventional and most commonly used circuit in Fig.1, a number of attractive features of the proposed DIMC can be noticed and summarized.

1. Three switches and the related drive circuits can be saved.
2. Large size electrolytic capacitor is eliminated to reduce the large size and to increase reliability and life time of DIMC.
3. Without the electrolytic capacitor, there is no need to control the fictitious dc-link voltage. The compact control loop will not degrade the converter performance due to the advanced modulation schemes. Detailed control algorithms of the converter will be elaborated in Section III.

It should be noted that the DIMC is not feasible for the case when the load voltage is lower than the source voltage. The summation of the voltage amplitudes of two input sources is less than the amplitude of the load voltages.

The maximum currents through the upper and lower switches of the Nine switch converter are the summation of the two input currents. For example, the currents flowing through ST1/ST3 will be i_A+i_R during state $ST_{1,2,3}$={110}/{011}. Current through the middle switch ST2 will be i_A/ i_R during state $ST_{1,2,3}$={110}/{011}.but not i_A+i_R. The DIMC will face higher current rating issues for switches compared with traditional solution in Fig.1 if the two input ac sources are generating their highest currents simultaneously. However, disadvantages for high switches current rating of the nine switch converter can be removed when considering two complementary input ac sources.

Two input three phase currents can extract their own commands according to the power dispatch order. Sinusoidal input and output currents under balanced ac supply and load conditions can be attained through the coordinated modulation schemes.

II. SYSTEM MODEL

The rectifier stage includes input filter to eliminate the high frequency component of the input currents and relevant the over voltages. For proper operation the rectifier must provide a positive dc-link voltage to the Nine-Switch Inverter. The rectifier has 15 different switching states and the input voltage is defined as,

$$v_{i\_up} = [v_{ia} \quad v_{ib} \quad v_{ic}]^T \qquad (1)$$

$$v_{i\_down} = [v_{ia} \quad v_{ib} \quad v_{ic}]^T \qquad (2)$$

The relationship between positive dc voltage and input voltages is given by

$$v_{DC} = \begin{bmatrix} s_{AU} & s_{BU} & s_{CU} \\ s_{AM} & s_{BM} & s_{CM} \\ s_{AL} & s_{BL} & s_{CL} \end{bmatrix} v_i \qquad (3)$$

The input current vector of the rectifier is defined as

$$i_{i\_up} = [i_{ia} \quad i_{ib} \quad i_{ic}]^T \quad (4)$$

$$i_{i\_down} = [i_{ia} \quad i_{ib} \quad i_{ic}]^T \quad (5)$$

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The relationship between the input current and dc link current is

$$v_{DC} = \begin{bmatrix} s_{AU} & s_{BU} & s_{CU} \\ s_{AM} & s_{BM} & s_{CM} \\ s_{AL} & s_{BL} & s_{CL} \end{bmatrix} v_i \qquad (6)$$

For the NSI topology, each leg has three switches and there are eight different ON-OFF positions. All switches on the same leg cannot be turned on at the same time to avoid DC bus short circuit. Another switching restriction is that at least two switches on the same leg should be on, so that floating of the connected load is avoided. Considering these switching restrictions, each leg can be in three different switch combinations which are called {1, 0, -1} [11]. Possible switch positions are illustrated in Table I with i= A, B and C identifying the inverter leg. The NSI has 27 possible switching states, but, since some of them are redundant, only 15 of these switching states are sufficient to control two ac loads independently [12].

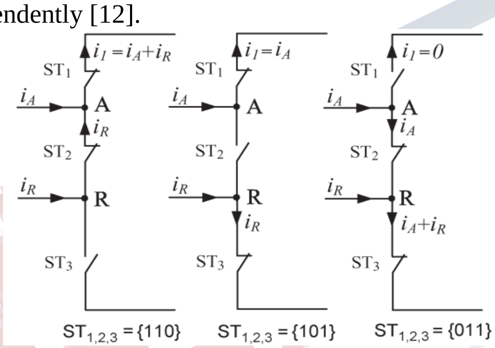

Fig.2. Three equivalent circuits for leg one of the Nine switch converter

Table 1
Switches positions of Legs

	$S_i = 1$	$S_i = 0$	$S_i = -1$
S_{iU}	ON	OFF	ON
S_{iM}	OFF	ON	ON
S_{iL}	ON	ON	OFF

The instantaneous transfer matrix of upper load TU is defined as

$$i_{i\_up} = \begin{bmatrix} i_{ia} & i_{ib} & i_{ic} \end{bmatrix}^T \qquad (7)$$

The relationship between output upper load voltage and the dc-link voltage is given by

$$v_{i\_up} = \begin{bmatrix} v_{ia} & v_{ib} & v_{ic} \end{bmatrix}^T \qquad (8)$$

The instantaneous transfer matrix of lower load TL is defined as

$$T_L = \begin{bmatrix} 1 - s_{AL} & 1 - S_{BL} & 1 - S_{CL} \end{bmatrix} \qquad (9)$$

The relationship between output lower load voltage and the dc-link voltage is given by

$$v_{i\_low} = \frac{V_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} T_L^T \qquad (10)$$

$$i_{DC} = T_U \begin{bmatrix} i_{oa\_up} \\ i_{ob\_up} \\ i_{oc\_up} \end{bmatrix} + T_L \begin{bmatrix} i_{oa\_low} \\ i_{ob\_low} \\ i_{oc\_low} \end{bmatrix} \qquad \mathbf{(11)}$$

INPUT FILTER AND LOAD: CONTINUOUS SYSTEM MODEL

The input filter shown in Fig. 1 can be represented by the
following equations:

$$V_s = L_f \frac{di_s}{dt} + R_f i_s + V_i \qquad (12)$$

$$i_s = i_i + C_f \frac{dV_i}{dt} \qquad (13)$$

The dynamics of the load current can be described by (14),
where *RL* is the load resistance and *LL* represents the load
inductance

$$V_0 = Ri_0 + L \frac{di_0}{dt} \qquad (14)$$

Discrete- time prediction model

Model predictive controller uses a discrete-time model of the system to form the load current for a sampling time Ts can be used to predict the future value of load current with the voltage measured current at the Kth sampling instant

Approximating the derivative $\frac{di_0}{dt}$ by

$$\frac{di_0}{dt} \approx \frac{i_0(k+1) - i_0(k)}{Ts} \qquad (15)$$

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Output load current prediction equations are obtained by using continuous time model of the RL circuit (13) and forward Euler approximation (15)

$$V_0 = Ri_0(k) + L\left[\frac{i_0(k+1) - i_0(K)}{Ts}\right] \quad \textbf{(16)}$$

$$V_0 Ts = TsRi_0(k) + L[i_0(k+1) - i_0(k)] \quad (17)$$

$$V_0 Ts - TsRi_0(k) = L[i_0(k+1) - i_0(k)] \quad (18)$$

$$V_0 \frac{Ts}{L} - \frac{Ts}{L} Ri_0(k) + i_0(k) = i_0(k+1) \quad (19)$$

$$i_0(k+1) = V_0 \frac{Ts}{L} + i_0(k)\left[1 - \frac{RTs}{L}\right] \quad (20)$$

Where the term R Ts could be neglected if the sampling period is small enough and the load is mainly inductive. Future values of the upper load and lower load currents, resulting in the following expression (21) and (22)

$$i_{0\_UP}(k+1) = V_{0\_UP} \frac{Ts}{L_{UP}} + i_{0\_UP}(k)\left[1 - \frac{R_{UP}Ts}{L_{UP}}\right] \quad (21)$$

$$i_{0\_LOW}(k+1) = V_{0\_LOW} \frac{Ts}{L_{LOW}} + i_{0\_LOW}(k)\left[1 - \frac{R_{LOW}Ts}{L_{LOW}}\right] \quad (22)$$

INPUT FILTER AND LOAD: DISCRETE SYSTEM MODEL

A discrete-time form of the input side for a sampling time *Ts* can be employed to estimate the future value of the input current considering the voltages and currents measurements at the *k*th sampling time. The second order input side filter can be represented by a state-space model with the variables **is** and **vi**:

$$\begin{bmatrix} \dot{V}_i \\ \dot{i}_s \end{bmatrix} = A_c \begin{bmatrix} V_i \\ i_s \end{bmatrix} + B_c \begin{bmatrix} V_s \\ i_s \end{bmatrix} \quad (23)$$

Where,

$$A_c = \begin{bmatrix} 0 & \frac{1}{C_f} \\ \frac{-1}{L_f} & \frac{-R_f}{L_f} \end{bmatrix} B_c = \begin{bmatrix} 0 & \frac{1}{C_f} \\ \frac{-1}{L_f} & 0 \end{bmatrix} \quad (24)$$

Assuming that,

$$\left.\begin{matrix} V_s = V_s(kT_s) = V_s[k] \\ i_i = i_i(kT_s) = i_i[k] \end{matrix}\right\} for kT_s \le t \le (k+1)T_s \quad 25)$$

Then the discrete time state-space model [16] is determined as follows:

$$\begin{bmatrix} V_i[k+1] \\ i_s[k+1] \end{bmatrix} = \Phi \begin{bmatrix} V_i[k] \\ i_s[k] \end{bmatrix} + \Gamma \begin{bmatrix} V_s[k] \\ i_s[k] \end{bmatrix} \quad (26)$$

Where

$$\Phi \cong \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} = e^{AT} \quad (27)$$

$$\Gamma \cong \begin{bmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{bmatrix} = \int_0^{Ts} e^{A_c(ts-\tau)} B_c \, d\tau \quad (28)$$

Hence, the input current and capacitor voltage can be easily derived using

$$V_i[k+1] = \Phi_{11}V_i[k] + \Phi_{12}i_s[k] + \gamma_{11}V_s[k] + \gamma_{12}i_i[k] \quad (29)$$

$$i_s[k+1] = \Phi_{21}V_i[k] + \Phi_{22}i_s[k] + \gamma_{21}V_s[k] + \gamma_{22}i_i[k] \quad (30)$$

Instantaneous reactive power can be calculated using discrete-time model of input filter model reactive power is defined as

$$Q[k+1] = V_{s\beta}[k+1]i_{s\alpha}[k+1] - V_{s\alpha}[k+1]i_{s\beta}[k+1] \quad (31)$$

Instantaneous reactive power is expressed in α-β frame and park transformation can be used to calculate real and imaginary parts of the associate vectors.

MPC scheme for dual output indirect matrix converter

Model Predictive control strategy has been implemented on a discrete time prediction model. The timing of the different tasks performed by discrete time prediction model is shown in fig-3.

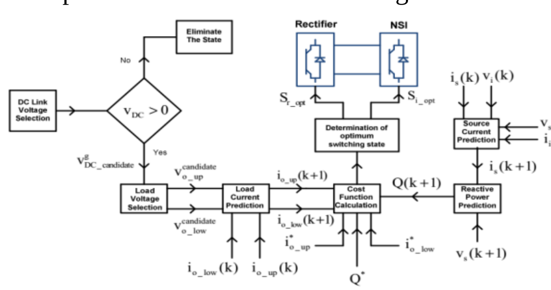

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Figure 3. Model Predictive Control Scheme for Dual Output Indirect Matrix Converter

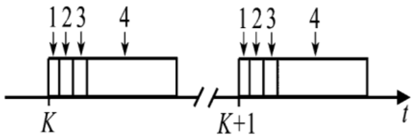

Fig .3 Timing of the different Tasks

1.Apply the new switching state
2.Measuring of currents
3.Load current prediction and switching state selection

In this MPC model, it is used to predict the future value of the controlled quantities for each possible switching states , so that appropriate switching states that can meets the desired output control objectives can be identified for upper load current control, lower load current control and minimization of the instantaneous reactive power . Upper and lower load current error for the next sampling instant can be expressed as follows

$$g_1 = \sqrt{\left|i^*_{0\alpha\_UP} - i_{0\alpha\_Up}\right|^2 + \left|i^*_{0\beta\_UP} - i_{0\beta\_UP}\right|^2} \quad (32)$$

$$g_2 = \sqrt{\left|i^*_{0\alpha\_LOW} - i_{0\alpha\_LOW}\right|^2 + \left|i^*_{0\beta\_LOW} - i_{0\beta\_LOW}\right|^2}$$

(33)

The reactive power term is expressed as

$$g_3 = \left|Q^* - Q\right| \quad (34)$$

For reactive power minimization, reference reactive power Q^* is set to zero. The cost function for this system contains all these three error terms and it is defined as

$$g = Ag_1 + Bg_2 + Cg_3 \quad (35)$$

Predictive control scheme is shown in Fig.3 and reference values for load currents and reactive power are denoted by superscript “*”. Constant A,B and C are the weighting factors. Three phase load currents are calculated in α-β frame and costs for the two ac load current errors are evaluated in this frame. The operation of the NSI stage. The state elimination process is responsible for selecting rectifier switching states that provide positive dc-link voltage. As a positive dc-link voltage are used to calculate future load currents.

VIII. SIMULATION RESULTS

The Dual input Dual output Indirect Matrix Converter was simulated using MATLAB Simulink. Simulation parameters are listed in table-2. Upper load currentsare shown in fig.4, lower load currents shown in fig.6 and source current are shown in fig.10. Source voltage for only one phase is shown in fig.5. According to the Simulation results good output load current tracking is obtained.

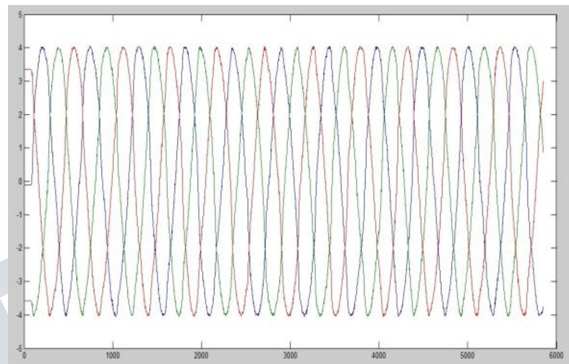

Fig.4 Upper Load Currents

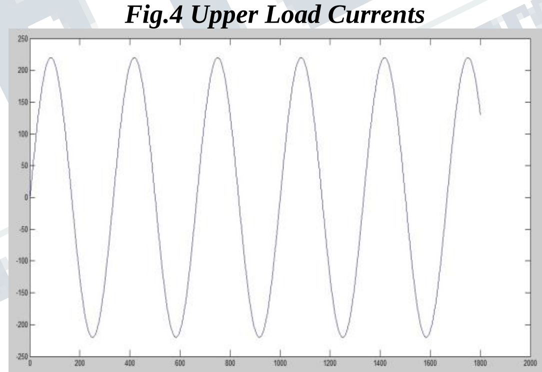

Fig.5 Source voltage for 1-phase

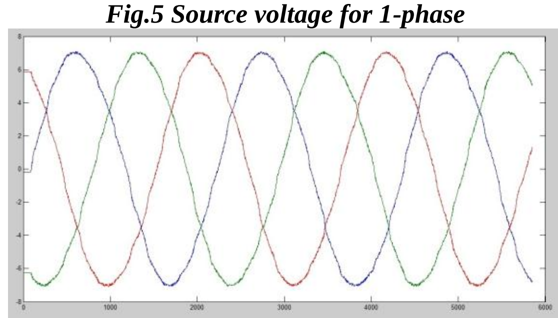

Fig.6 Lower Load Currents

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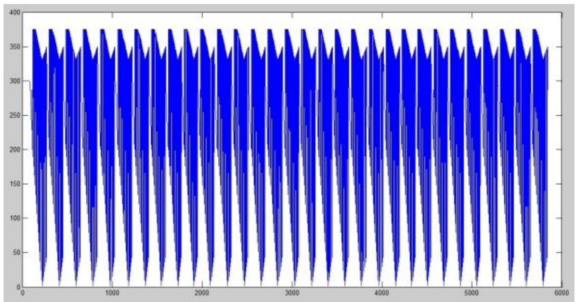

Fig.7 DC-Link Voltage

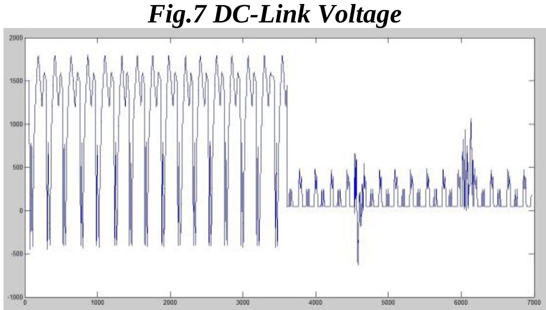

Fig.8 Source Current Instantaneous Reactive Power

In order to evaluate dynamic behavior of the predictive control technique, the system step response is shown in fig step response waveform shows that step response time for upper load (system step at t=0.0271) is 500µs which corresponds to 25 sampling steps and step response time for the lower load (system step at t=0.0423) is 800µs which corresponds to 40 system steps fig shows that predictive controller can provide both excellent dynamic and steady state performance.

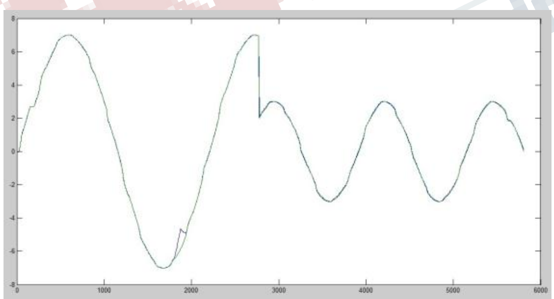

Fig.9 Step Response for upper load Predictive Controller

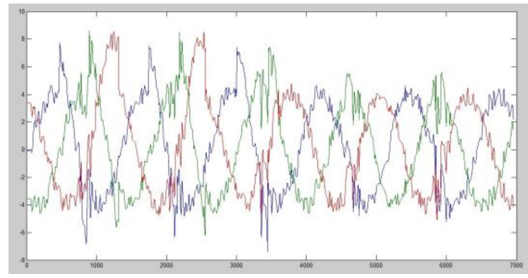

Fig.10 Source current

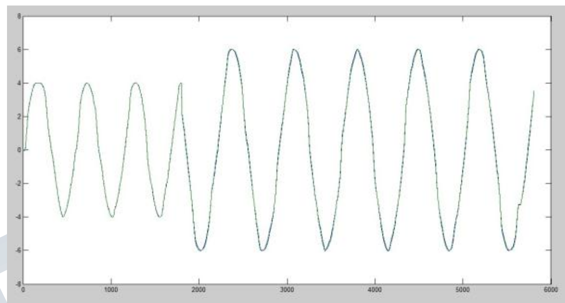

Fig.11 Step response for lower load predictive controller

Table-2
Simulation Parameters

Ts	20µs
Source Voltage	220 V peak/60Hz
RL load	10Ω
Rf	0.5Ω
Lf	145µH
Cf	32µF
Upper Load current Reference	4A/120 Hz
Lower Load Current Reference	7A/30Hz

CONCLUSION

As a result of the advances in power semiconductors and procedures, indirect matrix converter and predictive control schemes have recently emerged as feasible approaches. This model predictive control strategy and its implementation has been presented. It has been shown that the proposed method controls very effectively the load currents having a good dynamic response and steady state response. The implementation of control strategy is simple. This control scheme uses a discrete-time model of the converter and predicts load current and reactive power to determine the best suited switching combination by solving a multi objective optimization problem. The proposed strategy avoids the use of linear and nonlinear controllers. In addition, it is not necessary to include any type of modular. The drive signals for the IGBTs are generated directly by the controller. MPC technique is tested for different control objectives and it performs well under the different condition. New control objectives can be added in the cost function and controlled simultaneously.

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