

# High Performance Current Controller for Sparse Matrix Converter Based on Model Predictive Control

Eunsil Lee\*, Kyo-Beum Lee<sup>†</sup>, Young Il Lee\*\* and Joong-Ho Song\*\*\*

**Abstract** – A novel predictive current control strategy for a sparse matrix converter is presented. The sparse matrix converter is functionally-equivalent to the direct matrix converter but has a reduced number of switches. The predictive current control uses a model of the system to predict the future value of the load current and generates the reference voltage vector that minimizes a given cost function so that space vector modulation is achieved. The results show that the proposed controller for sparse matrix converters controls the load current very effectively and performs very well through simulation and experimental results.

**Keywords:** AC-AC power conversion, Sparse matrix converter, Load current control, Predictive control

## 1. Introduction

The matrix converter is an AC-AC direct power conversion system that allows bidirectional power flow, and it converts a voltage with a variable amplitude and frequency from a constant voltage of magnitude and frequency. The matrix converter has no energy storage in the dc-link stage and operates with unity power factor for any load. Compared with a traditional converter, it has many advantages such as; 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 the unity power factor for any load; 5) regeneration capability [1]. The three-phase matrix converter utilizes eighteen unipolar turn-off power semiconductors such as insulated gate bipolar transistors (IGBTs) and eighteen diodes or nine bidirectional switches for connecting the input phases to the output phases.

Until now, numerous techniques in this field, with regard to matrix converters, were developed. An indirect matrix converter topology is proposed where a current-source rectifier is directly connected to a voltage-source inverter without any intermediate energy storage element. From indirect matrix converter topology, the sparse matrix converter topologies are derived [2]. These topologies are functionally-equivalent to the standard indirect matrix converter but have reduced number of switches. Since the matrix converter has the drawback of low voltage ratio (max. 0.866), a novel matrix converter is proposed in [3].

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In order to overcome the inherent drawback of the low voltage transfer ratio of the conventional matrix converter, a Z-source network is employed. Recently, the increase of reliability and fault tolerance of power converters are becoming more and more important. The fault tolerance method involves the fault detection, fault location, fault isolation, and reconfiguration of the system so that the converter is able to continue to run even with the degraded performance [4~6].

As power converters with control schemes increase, current control strategy has been developed since the second half of the 20th century. Linear controllers, like proportional-integral (PI) controllers and nonlinear methods, like hysteresis control have been the most widely developed control strategies for power converters [7]. Adapted with discrete time digital implementation, these controllers are widely used in the industry. On the other hand, the development of powerful and fast digital signal processors makes possible the implementation of more complex control techniques such as model predictive controls. The model predictive control can be considered as any algorithm that uses a model of the system for calculating prediction of the future behavior and choose the most optimal value based on a control variable [8]. Predictive control has several advantages as follows: 1) concepts are intuitive and easy to understand; 2) it can be applied to a variety of systems; 3) a multivariable case can be considered; 4) the resulting controller is easy to implement. However, some implementation of predictive control, in order to make it more robust, can be more complex compared to a classical control scheme. Also this method requires parameters of the system. This model predictive control can be used to control a voltage source inverter, a matrix converter, a neutral point clamped inverter, and etc. [9~13].

This paper presents the method of predictive current

controller having the theoretical simplicity, good quality of load current, fast dynamic response and flexibility applied to a sparse matrix converter. The predictive approach is based on the model of the system to predict the load current and this generates the reference voltage vector that minimizes a given cost function. The paper is organized in several sections: the sparse matrix converter topology, which a reduced number of power semiconductors, is presented in section 2. This section explained the modulation of the power converter in details. Section 3 presents a predictive current control strategy for a sparse matrix converter. The effectiveness of the overall controlled system is verified using PSIM and experiment considering different reference current as given in section 4. Finally, in section 5 the contributions of the paper are summarized with concluding remarks.

## 2. System Description

This section presents the topology of sparse matrix converter. The three-phase sparse matrix converter topologies are developed based on the structure of an indirect matrix converter. It can be classified according to a number of switches: sparse matrix converter (SMC), very sparse matrix converter (VSMC), and ultra sparse matrix converter (USMC). In this paper, the sparse matrix converter is considered as a very sparse matrix converter. The three-phase sparse matrix converter employs 12 IGBTs and 30 diodes as shown in Fig. 1. It can be observed that the rectifier stage is connected to the inverter stage via imaginary dc-link without any energy storage element. To decouple the converter from the utility grid, an LC filter is inserted between the converter and utility grid to attenuate high harmonics generated by the switch. In the rectifier stage, each combination of one semiconductor device and four diodes functions as a bidirectional switch. The inverter stage is the same as the conventional six-switch inverter.

The aim of the modulation in rectifier stage is to produce maximum voltage in the dc-link as well as to maintain the

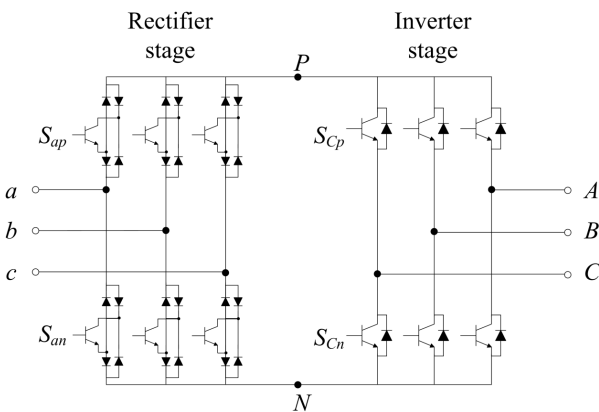


Fig. 1. The three-phase sparse matrix converter

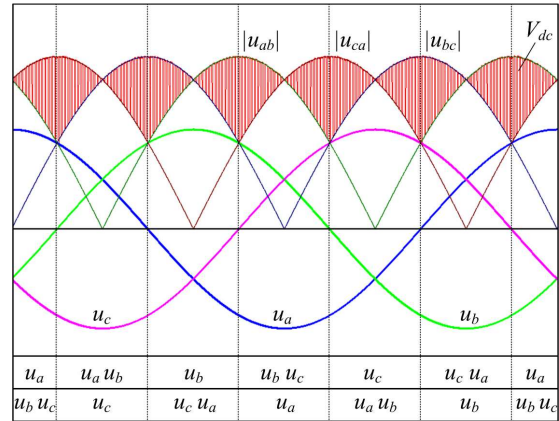


Fig. 2. The dc-link voltage and input voltage

sinusoidal input current and unity input power factor. The converter synthesizes a positive voltage in dc-link stage by selecting a switching state in the rectifier stage. Through the switching state, one phase of input sources is connected to the point  $P$  and the other phase to the point  $N$  in Fig. 2. For example in the interval from  $-\pi/6$  to  $\pi/6$ , the instantaneous input voltage  $u_a$  is positive and the upper switch of phase  $a$  stays on, while the input voltages  $u_b$  and  $u_c$  are negative and the lower switches of phase  $b$  and  $c$  are modulated to achieve the maximum voltage of dc-link. All other switches keep in off state in this region. Therefore, the dc-link voltage is formed by switching the rectifier stage between the largest and the second largest line-to-line input voltages. If the phase angle between the space vector of the input voltage and current is set to zero, a unity displacement factor is achieved.

The inverter stage of the sparse matrix converter utilizes the conventional six-switch inverter. The inverter stage should be switched into a free-wheeling state and then the rectifier stage could commutate with zero current in dc-link stage. Therefore the commutation sequence of the power switches is very important for the sparse matrix converter topologies. If the current is flowing from the dc-link stage to the load, the switching state of the rectifier stage cannot be changed. Thus a commutation sequence is necessary to avoid shorting the input phases and safely changing from one state to another. In the inverter stage, the output voltage formation of traditional inverter space vector pulse width modulation (SVPWM) technique is achieved. In addition, it can be seen that the inverter switching frequency is twice of the rectifier switching frequency as a full switching cycle of the inverter is contained in each rectifier pulse half interval.

## 3. Predictive Control of Sparse Matrix Converters

Considering the growing requirements in performance and efficiency of matrix converters and drives, the

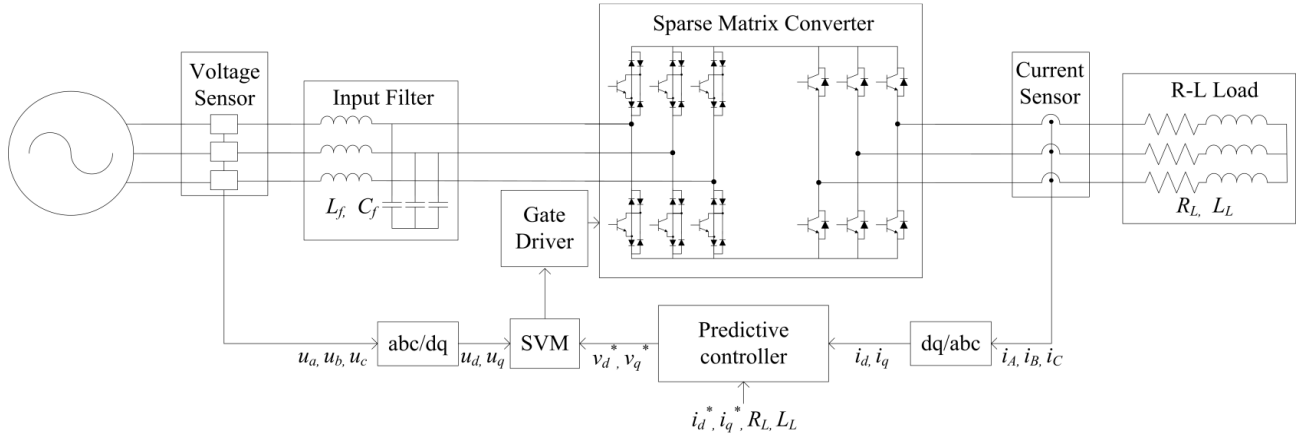


Fig. 3. A diagram of the sparse matrix converter system using the predictive controller

development of a novel control strategy must take into account the real nature of these kinds of systems. The matrix converters are nonlinear systems, including linear and nonlinear parts. For the controller, the constraints and restrictions have to be considered. Some of these new control schemes for matrix converters include fuzzy, neural networks, sliding mode control, and predictive control techniques. Fuzzy logic is befitting for applications where the controlled system's parameters are unknown. Sliding mode control provides robustness and considers the switching nature [15].

These days, actual control strategies are realized in digital control platforms running at discrete time steps. Control platforms offer an increasing computational capability and more calculation-demanding control algorithms are becomes practical today. This is the main reason to choose the predictive control.

This section presents the predictive control technique for sparse matrix converter systems. A block diagram of the predictive current control scheme for the sparse matrix converter is shown in Fig. 3 considering an RL load. The model of load is used to calculate the future values of the output current. Based on these predictions, a cost function is used for the selection of the optimal switching state. Moreover, our algorithm is considering the limitation of input voltages.

The control scheme presented in the subsequent section is categorized into two: the predictive control equations using the model of the system and specific condition which has constraint of the amplitude of the output voltage.

### 3.1 Design of the output current controller

As the sparse matrix converter consists of a rectifier stage connected the inverter stage without any energy storage element in the dc-link stage, the mathematical model can be classified into the rectifier and inverter stage. In the rectifier stage, in order to make the maximum voltage, a phase input voltage is clamped to the dc-link when the corresponding phase voltage has the highest

absolute value. The dc-link voltage is defined by segments of the input voltage according to the rectifier switching state.

Assume the load has an inductive-resistive characteristic as shown in Fig. 3. The voltage equation of the system can be described by the following equation, where  $R_L$  is the load resistance and  $L_L$  is the load inductance and  $i_{ABC}$  is the load current;

$$V_{ABC} = R_L i_{ABC} + L \frac{di_{ABC}}{dt} \quad (1)$$

where  $v_{ABC} = [v_A \ v_B \ v_C]^T$ ,  $i_{ABC} = [i_A \ i_B \ i_C]^T$ . Applying the  $d$ - $q$  transformation to (1) in a stationary reference frame,

$$\begin{aligned} V_{ds} &= R_L i_{ds} + L_L \frac{di_{ds}}{dt} \\ V_{qs} &= R_L i_{qs} + L_L \frac{di_{qs}}{dt} \end{aligned} \quad (2)$$

where currents  $i_d$  and  $i_q$  are the real and imaginary parts of the current.

The measurements and system model described in Eq. (2) is used to predict during the next sampling time, the value of the output current for switching state. After the transformation to rotating reference frame, using a differential approximation, the predictive value of the load current  $i_d$  and  $i_q$  can be expressed in discrete time form with output currents measured at the time  $t=k$

$$\begin{aligned} i_d(k+1) &= a i_d(k) + b v_d(k) \\ i_q(k+1) &= a i_q(k) + b v_q(k) \end{aligned} \quad (3)$$

where

$$\begin{aligned} a &:= e^{-R_L T_s / L_L} \\ b &:= (1 - e^{-R_L T_s / L_L}) / R_L. \end{aligned} \quad (4)$$

The approach searches for selection of the switching

state that leads the output currents closest to their respective references. Using the error between the reference value and predicted load current, the cost function  $J(k)$  can be expressed as follows,

$$J(k) = \|\bar{i}_o^* - \bar{i}_o(k+1)\|^2 \quad (5)$$

$$\equiv (\bar{i}_o^* - \bar{i}_o(k+1))^T (\bar{i}_o^* - \bar{i}_o(k+1))$$

where  $\bar{i}_o^*$  is a space vector of reference output current.

For the final step, the predicted values are used to evaluate a cost function  $J(k)$ . In order to control the load current, the cost function should be minimized. The above expression can be represented regarding space vector of output voltage  $\bar{v}_o$  as follows,

$$J_k(\bar{v}_o) = A\bar{v}_o^2 + B\bar{v}_o + C \quad (6)$$

where  $A = b^2$ ,  $B = 2b(a\bar{i}_o^* - \bar{i}_o^*)$ , and  $C = (\bar{i}_o^* - a\bar{i}_o^*)^2$ .

Suppose the following expression about any vector  $\bar{x}$  and scalar  $d$ ,

$$J_k(\bar{v}_o) = A(\bar{v}_o + \bar{x})^2 + d \quad (7)$$

when  $\bar{v}_o = -\bar{x}$ ,  $J_k(\bar{v}_o)$  has a minimum value of  $d$ .

To demonstrate this point, (7) can be represented and compared with (6),

$$J_k(\bar{v}_o) = A\bar{v}_o^2 + 2A\bar{x}\bar{v}_o + A\bar{x}^2 + d \quad (8)$$

$$\therefore \bar{v}_o = -\frac{B}{2A}. \quad (9)$$

Thus it is easy to see the reference output voltage as,

$$v_d^* = \frac{(i_d^* - ai_d(k))}{b}, \quad v_q^* = \frac{(i_q^* - ai_q(k))}{b}. \quad (10)$$

### 3.2 Constraint of the control

Given the reference output voltage of matrix converter, the output voltage from the modulation can be generated accurately. However, depending on the modulation method, there is a limit to the range of output voltage in which it can be generated linearly. In particular, if the reference output voltage of matrix converter exceeds more than the output voltage of 0.866 times, the output voltage cannot be exactly generated. In this modulation range, the linearity of the output voltage on the reference voltage shatters because the output voltage is generated less than the reference voltage. As a result, as the performance of the voltage control is distorted and harmonics increases, the performance of the entire system will decrease. Therefore, given the reference voltage which exceeds the range that can possibly be generated linearly, through adequate technique the reference output voltage

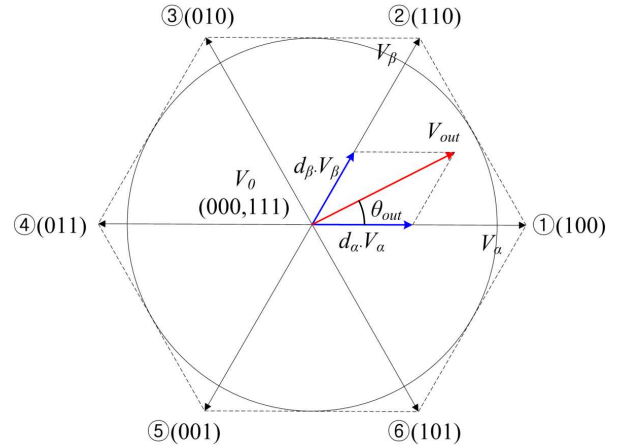


Fig. 4. The output space vector hexagon

has to be controlled.

In matrix converter, the output switching vectors are located in six directions as can be seen in Fig. 4. The magnitude of output switching vectors is defined as the actual dc-link voltage which is decided by the switching state of the rectifier. These six combinations (100, 011, 001, 101) and two zero vectors (000, 111) synthesize the output voltage space vector with duty ratio  $(d_\alpha, d_\beta)$ . When the reference vector is within the hexagon, the output is synthesized using the vectors defined on the border of the sector. Thus the reference output voltage space vector draws a circular trajectory inside the switching hexagon. The maximum amplitude of the reference vector equals the radius of the inner circle of the hexagon. Suppose that the admissible maximum voltage is confined in a radius  $r$ . Then the output voltage space vector should belong to

$$\nu = \{\bar{v}_o : \|\bar{v}_o\|^2 \leq r^2\}. \quad (11)$$

If  $v_o^* \in \nu$ , the output voltage reference vector is defined by (10). Otherwise, the optimal solution will be located on the boundary of  $\nu$ . Hence,

$$\|\bar{v}_o^*\|^2 = \bar{v}_o^{*T} \bar{v}_o^* = r^2. \quad (12)$$

Given the constraint above, the optimal solution can be obtained through the Lagrange multipliers method [16]. Suppose there exists a real number  $\mu$ . such that

$$\frac{\partial J(k)}{\partial \bar{v}_o} = \mu \frac{\partial (\|\bar{v}_o\|^2 - r^2)}{\partial \bar{v}_o}. \quad (13)$$

Here,  $\partial J(k) / \partial \bar{v}_o$  represents the gradient of  $J(k)$  with respect to  $\bar{v}_o$ . After some calculations using (12) and (13), the Lagrange constant  $\mu$  and the optimal solution  $\bar{v}_o^*$  can be obtained as,

$$\bar{v}_o^* = \frac{\bar{i}_o^* - \bar{i}_o(k)}{\|\bar{i}_o^* - a\bar{i}_o(k)\|} r. \quad (14)$$

### 3.3 Design of the input current controller

In order to predict the value of input current, an adequate model of the filter inductor current is and filter capacitor voltage  $v_i$  is indispensable [14].

$$\frac{di_i(t)}{dt} = \frac{1}{L_f}(v_s(t) - v_i(t)) - \frac{R_f}{L_f}i_s(t) \quad (15)$$

$$\frac{dv_i(t)}{dt} = \frac{1}{C_f}(i_s(t) - i_i(t)) \quad (16)$$

where,  $C_f$  represents the filter capacitance,  $L_f$  is the filter inductance and  $R_f$  represents the filter damping resistance.

A discrete-time form of the input current can be employed to estimate the future value of the input current considering the voltages and currents measurements. In the same way as before, the input current can be easily derived using

$$i_s(k+1) = \phi_{21}v_i(k) + \phi_{22}i_s(k) + \gamma_{21}v_s(k) + \gamma_{22}i_i(k) \quad (17)$$

where,

$$\Phi \cong \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} = e^{AT_s} \quad (18)$$

$$\Gamma \cong \begin{bmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{bmatrix} = A^{-1}(\Phi - I)B \quad (19)$$

$$A = \begin{bmatrix} 0 & 1/C_f \\ -1/L_f & -R_f/L_f \end{bmatrix}, \quad B = \begin{bmatrix} 0 & -1/C_f \\ 1/L_f & 0 \end{bmatrix}. \quad (20)$$

## 4. Simulation and Experimental Results

This section evaluates performance and effectiveness of the proposed control strategy, based on time-domain simulations in the PSIM environment. The parameters of the simulated system of Fig. 3 are listed in Table 1.

**Table 1.** Parameters of matrix converter system

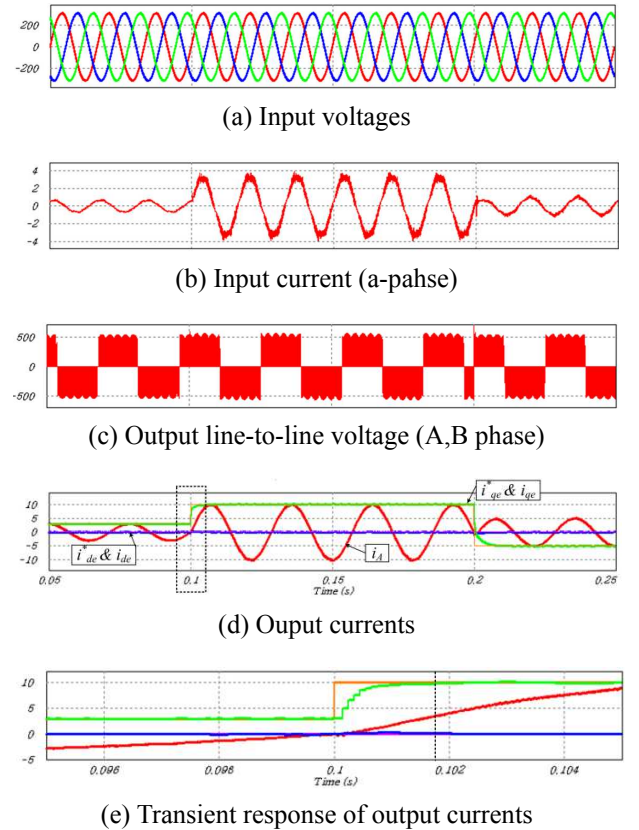
Parameter	Symbol	Value
Voltage of grid	$V_g$	380 $V_{rms}$
Frequency of grid	$F_g$	60 Hz
Damping resistor	$R_f$	0.01 $\Omega$
Inductance of filter	$L_f$	1.2 mH
Capacitor of filter	$C_f$	6 $\mu F$
Resistor of load	$R_L$	10 $\Omega$
Inductance of load	$L_L$	30 mH

The input capacitors combined with the inductance of the feeding line forms a second order filter for the input current. We considered the RL load in this paper because most of the load has an inductive characteristic. The inductive load causes the phase shift between induced voltage and current, while the current maintains sinusoidal waveforms due to the linear impedance.

Simulation and experimental results are to evaluate the performance of the predictive control algorithm during the transient state. A comparison of the predictive current control to the classical PI control is presented in Fig. 5 and Fig. 6. The sparse matrix converter system is operating in steady state condition with  $I_{qe}^* = 3$  A and  $I_{qe}^* = 0$  A. At  $t = 0.1$  s,  $I_{qe}^*$  is stepped up from 3 A to 10 A and at  $t = 0.2$  s,  $I_{qe}^*$  is stepped down from 10 A to -5 A.

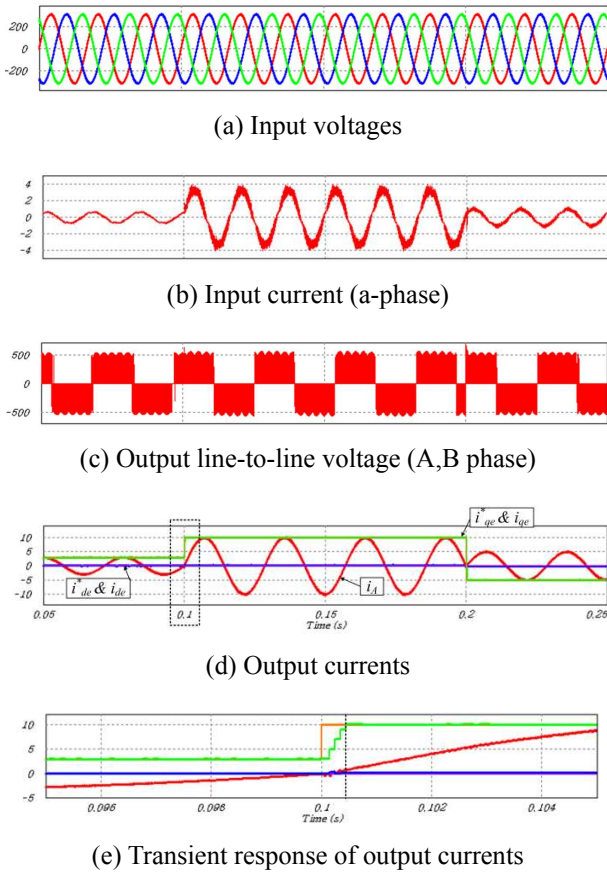
In the first test case, Fig. 5 illustrates the waveforms of the input voltages, the dc-link voltage, output line-to-line voltage and the output currents obtained from a sparse matrix converter, in the case of operating with PI the controller. In the second test case, the predictive current controller shown in Fig. 6 is used to control the load currents of the sparse matrix converter for the same test. The algorithm described in section 3 is implemented.

The load currents obtained using the PI controller, shown in Fig. 5(d), have a slower; however, the predictive control is shown in Fig. 6(d) and its dynamic response is very fast.

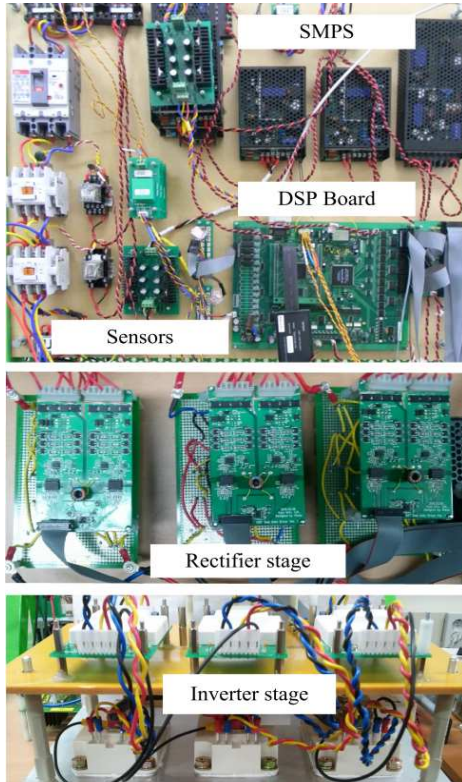


**Fig. 5.** Current control using PI controller

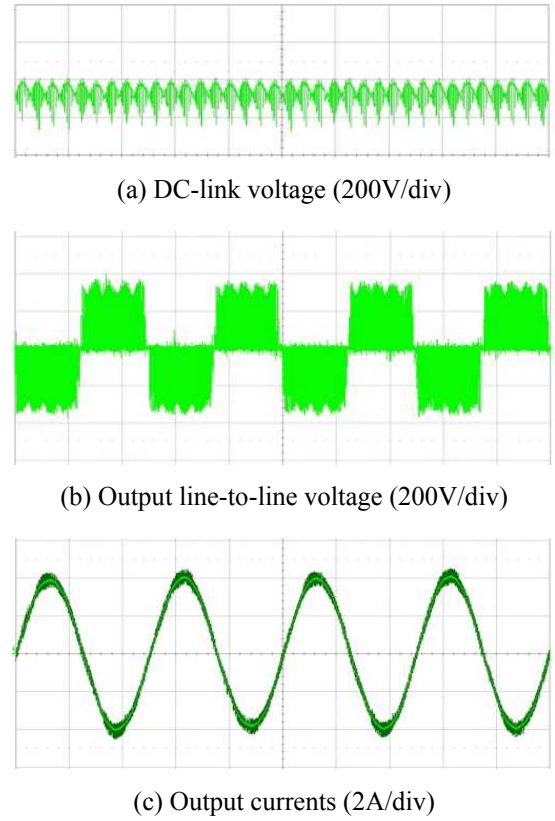




**Fig. 6.** Current control using predictive controller



**Fig. 7.** Experiment set of sparse matrix converter



**Fig. 8.** Basic operation mode of sparse matrix converter

Figs. 5(e) and 6(e) are magnified images from Fig. 5(d) and 6(d). The output currents take about 1.7 ms to reach the steady state in Fig. 5, but the output currents take about 0.5 ms in Fig. 6. Through this, it can be observed that the predictive current controller traces the reference very well and has fast transient response when the load current changes.

If a variation in parameters of the system such as load unbalance occurs depending on the time, the quality of output has a direct influence. Thus, some adaptation or estimation algorithm for robustness should be considered.

An experimental setup was developed using a TMS320F28335 DSP board. The sampling period of the control algorithm was set at  $T_p = 100 \mu s$ . The system parameters are the same as the simulation conditions. Fig. 7 shows the sparse matrix converter system, including the rectifier and inverter stage. The sparse matrix converter consists of 12 IGBTs and 30 diodes. Fig. 8 shows the basic operation of the sparse matrix converter. The rectifier stage has to produce a dc-voltage and the inverter stage generates the output currents. Figs. 9 and 10 show the load current of sparse matrix converter with PI and predictive current controller, respectively. There are the current of phase  $A$ , current of  $d$ -axis, and current of  $q$ -axis. In Fig. 9, the load currents present obvious coupling between  $i_{de}$  and  $i_{qe}$  and a slower response because of the dynamics of the closed current loops. For the same test, the response of the predictive current control shown in Fig. 10 is fast with a

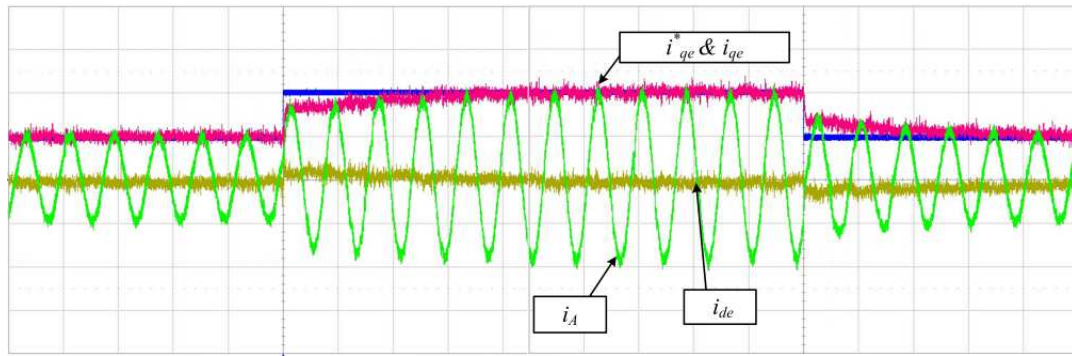


Fig. 9. Waveforms of the load current by PI controller

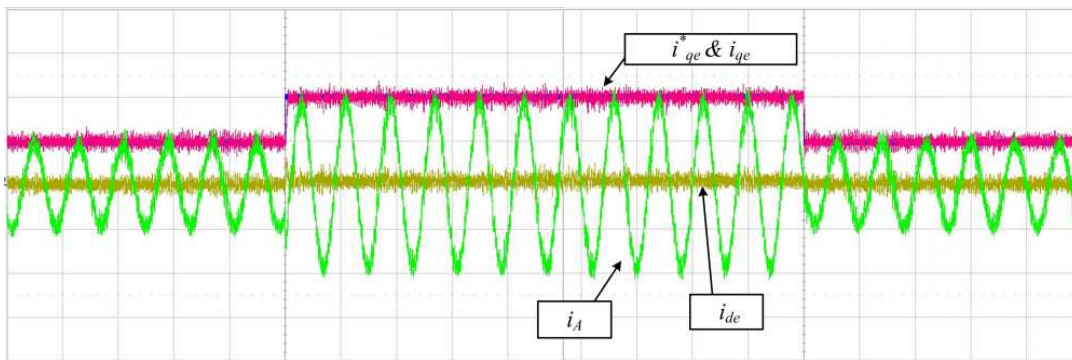


Fig. 10. Waveforms of the load current by predictive controller

decoupling between both current components.

Thus the advantages of this method are the simplicity of the implementation and good transient response.

## 5. Conclusion

A high performance current control strategy and its application for sparse matrix converter with a model predictive control is presented in this paper. This control uses a model of the system by measuring and calculating parameters and predicts the value. Detailed control method is presented in this paper based on the conventional SVPWM. Simulation and experimental results verify the effectiveness of the proposed controllers for different reference of current. It has been shown that the proposed method has a good dynamic response by controlling the load currents. The strategy introduced in this paper is very simpler than the classical control scheme and powerful for the sparse matrix converter. This method does not require any kind of linear controller and it can be applied to any type of converter and variables to be controlled.

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