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# Direct Torque Control Strategy of PMSM Employing Ultra Sparse Matrix Converter

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**ABSTRACT**

Matrix converter is a good choice for Permanent Magnet Synchronous Motor (PMSM) drives, because it has high power density and does not require dc-link energy storage. the disadvantages of conventional matrix converter is using 18 active switches, so it becomes expensive and the modulation method becomes more complicated than back to back converter. To minimize this problem, this paper proposes variable speed drive of PMSM using Ultra Sparse Matrix Converter (USMC) based on Direct Torque Control (DTC) methods. This converter uses only 9 active switches, making it cheaper than conventional matrix converter. DTC is designed based on Space Vector Modulation (SVM) to reduce torque and flux ripples due to the hysteresis control in conventional DTC. The simulation results show that DTC based SVM using USMC effectively controls the rotor speed with low torque and flux ripples.



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## 1. INTRODUCTION

Recently, Permanent Magnet Synchronous Motor (PMSM) widely used for variable speed drive in industrial applications, because it has advantages such as high power density with compact size, high efficiency and better dynamic performance than induction machines [1-7]. Variable speed control of PMSM typically using power converter as driver. Matrix converter have received more attention for variable speed drive of PMSM at last decade, because it has advantages such as free of the DC-link energy storage, high power density, adjustable input power factor and can generate sinuasoidal input and output waveforms [8-13]. One disadvantage of the conventional matrix converter is requires more active switches and the modulation technique becomes more complicated due to the switch structure in matrix form. To solve this problem, several types of indirect matrix converter have been developed in [9]. One of converter is a Ultra Sparse Matrix Converter (USMC). This converter uses only 9 active switches, which consist of the rectifier stage with 3 active switches and the inverter stage with 6 active switches. This makes UMSC cost less expensive than conventional matrix converters. The USMC structure consisting of two stage of converters makes the modulation technique simpler than conventional matrix converter by using Space Vector Modulation (SVM) method. In this method, the rectifier stage is modulated based on the input current vector, while the inverter stage is modulated based on the output voltage vector. Due to advantageous features, the USMC is proposed as a driver of a PMSM.

Variable speed control of PMSM generally using vector control methods, i.e. Field Oriented Control (FOC) [4-6] and Direct Torque Control (DTC) [14-16]. DTC has been widely applied for variable speed control of PMSM, because it has advantages such as faster torque dinamic response, simpler than FOC and easy to implement [14-17]. DTC is one method of electric machine speed control based on decoupled control of torque and flux. Variable speed control of PMSM based on DTC has been applied by using conventional matrix converter in [3,13]. In this paper, DTC is applied by using USMC, so the converter cost can be minimized. Modulation of matrix converter in [3] is designed based on switching tables with torque and flux regulations using hysterisis control method. it makes the modulation algorithm becomes complicated and produces high torque and flux ripples. To minimize the modulation complexity of the converter, the DTC system is proposed using SVM method to replace the switching table in conventional DTC. This method can also reduce the torque and flux ripples [14].

## 2. DIRECT TORQUE CONTROL OF PMSM USING ULTRA SPARSE MATRIX CONVERTER

The proposed DTC system for variable speed control of PMSM by using USMC as driver is shown in Fig.1. The system consists of PMSM, USMC, capacitor filter and controller. The rectifier stage of USMC is placed on the side of the power supply, while the inverter stage is placed on the side of PMSM. The USMC switches is modulated by using two SVMs. The switches of rectifier stage is modulated based on the input current vector, while the inverter stage is modulated based on the reference of output voltage vector.

The proposed DTC system for variable speed of PMSM is applied by regulating the error of electromagnetic torque and the error of flux linkage by using PI controller to obtain the output voltage reference in dq-axis (vd*,vq*) for modulation of inverter stage. The error of electromagnetic torque is obtained by comparing the reference of electromagnetic torque Te* with estimated electromagnetic torque Te. The Te* is obtained from speed control by regulating the error of rotor speed using PI controller, whereas the Te is calculated from the stator current, as shown in Figure 1. The error of flux linkage is obtained by comparing the reference of flux linkage ψs* with the estimated values ψs. The value of ψs* is assumed to be equal to flux linkage of permanent magnet ψf.

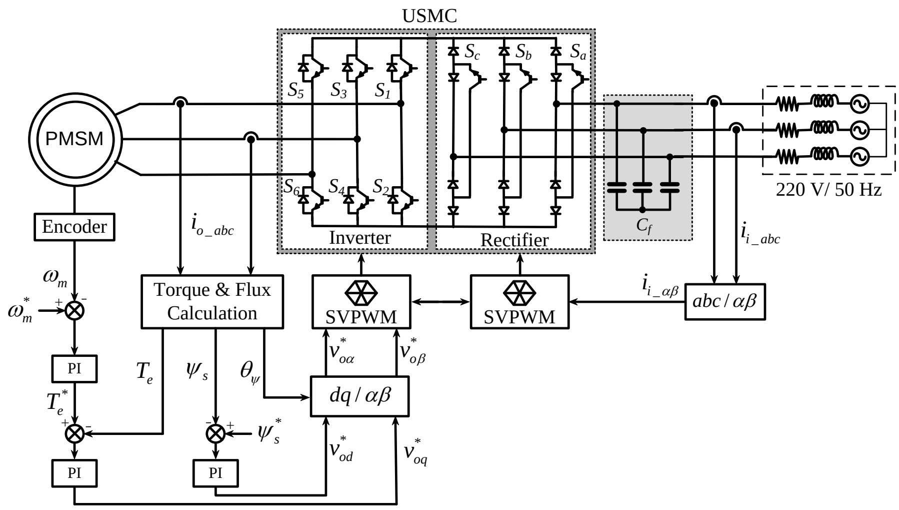



Figure 1. DTC scheme of PMSM using USMC

### a. Permanent Magnet Synchronous Motor

Direct Torque Control is applied with decoupled control of flux and torque in the rotating d-q reference frame. The dynamic model of PMSM in the rotating d-q reference frame can be written as :

$$v_d = R_s\ i_d - p\ \omega_m\ \psi_q + \frac{d\psi_d}{dt}$$
$$v_q = R_s\ i_q + p\ \omega_m\ \psi_d + \frac{d\psi_q}{dt} \tag{1}$$

where vd, vq are dq-axis stator voltages, id, iq are dq-axis stator currents, Rs, $\omega_m$ and p are the stator resistance, the rotor speed and the number of pole pairs, respectively. $\psi_d$ and $\psi_q$ are the dq-axis stator flux linkages. It can be calculated with :

$$\psi_d = L_d i_d + \psi_f$$
$$\psi_q = L_q i_q \tag{2}$$

where Ld, Lq are the stator inductances and $\psi_f$ is the flux linkage of permanent magnet. The mechanical dynamics and the electromagnetic torque Te of PMSM can be written as:

$$\frac{d\omega_m}{dt} = \frac{T_e - T_L - B\omega_m}{J} \tag{3}$$

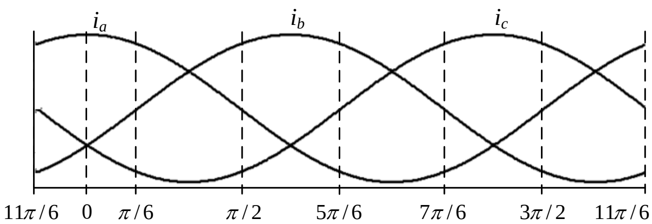
$$T_e = \frac{3}{2} p\left(\psi_d i_q - \psi_q i_d\right) \tag{4}$$

where Te, TL, B and J are the electromagnetic torque, the load torque, friction coefficient and inertia moment, respectively.

**2.2 Ultra Sparse Matrix Converter**

Ultra sparse matrix converter (USMC) is the simplest variant of sparse matrix converter developed from indirect matrix converter in [9]. This converter consists of the rectifier stage with 3 unidirectional active switches and the inverter stage with 6 bidirectional active switches, as shown in Figure 1. The rectifier stage and the inverter stage are separated by dc link without energy storage, so the modulation strategy becomes easier than direct matrix converter. This topology is functionally equivalent to a standard indirect matrix converter but has a reduced number of active switches [11,18]. The main difference between the USMC with another sparse matrix converters that the USMC only permits unidirectional power flow due to the structure of the rectifier switches [19].

The USMC switches is modulated using strategy which synchronizes the switching of the rectifier switches and the inverter switches to reduce switching losses [19]. The inverter switches can be switched into a free-wheeling state and then the rectifier switches can be commutate with zero dc-link current [9]. The USMC switches generally are switched by using space vector modulation method, specifically the rectifier switches are modulated based on the input current vector, while the inverter switches are modulated based on the output voltage vector [9,11].




| Sector / Switch | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $S_a$ | 1 | $d_{\alpha i} = -\frac{i_a}{i_c}$ | $d_{\beta i} = -\frac{i_a}{i_b}$ | 1 | $d_{\alpha i} = -\frac{i_a}{i_c}$ | $d_{\beta i} = -\frac{i_a}{i_b}$ |
| $S_b$ | $d_{\alpha i} = -\frac{i_b}{i_a}$ | $d_{\beta i} = -\frac{i_b}{i_c}$ | 1 | $d_{\alpha i} = -\frac{i_b}{i_a}$ | $d_{\beta i} = -\frac{i_b}{i_c}$ | 1 |
| $S_c$ | $d_{\beta i} = -\frac{i_c}{i_a}$ | 1 | $d_{\alpha i} = -\frac{i_c}{i_b}$ | $d_{\beta i} = -\frac{i_c}{i_a}$ | 1 | $d_{\alpha i} = -\frac{i_c}{i_b}$ |

Figure 2. Switching strategy of the rectifier switches

The switching strategy of the rectifier switches are designed to generate maximum dc-link voltage and keep unity input power factor. In this method, the phase angle between the input current and the input voltage is set to zero and the modulation index is set to 1. The status of the rectifier switches are determined by the input current vector that are divided into 6 sectors, as shown in Figure 2. The duty cycle of the rectifier switches for each sector can be calculated based on the input current vector as shown in Figure 2. For example, the duty cycle of the rectifier switches for sector 1 in $\alpha\beta$ can be written as :

$$d_{\alpha i} = -\frac{i_b}{i_a}, \quad d_{\beta i} = -\frac{i_c}{i_a}, \text{ and } d_{\alpha i} + d_{\beta i} = 1 \tag{5}$$

$d_{\alpha i}$ and $d_{\beta i}$ are the duty cycle in αβ-axis. The average dc link voltage can be formulated based on the duty cycle as follow :

$$\bar{V}_{dc} = v_\alpha \, d_{\alpha i} + v_\beta \, d_{\beta i} \tag{6}$$

$v_\alpha$ and $v_\beta$ are the input voltages in αβ-axis. The status of the inverter switches are determined by the output voltage vector that are separated by 6 sectors, as shown in Figure 3. Duty cycle of the inverter switches in αβ-axis can be written as :

$$d_{\alpha o} = M_o \sin\left(\frac{\pi}{3} - \theta_o\right), \quad d_{\beta o} = M_o \sin\left(\frac{\pi}{3}\right) \text{ and } d_{0o} = 1 - d_{\alpha o} - d_{\beta o} \tag{7}$$

$\theta_o$ is the output voltage angle and Mo is the modulation index, which can be calculated by :

$$M_o = \frac{V_o}{V_i} \le \frac{\sqrt{3}}{2} \text{ and } \theta_o = \tan^{-1}\frac{v_{o\alpha}}{v_{o\beta}} \tag{8}$$

Vi and Vo are the input voltage amplitude and the output voltage amplitude, respectively. $v_{o\alpha}$ and $v_{o\beta}$ are the αβ-axis output voltages.

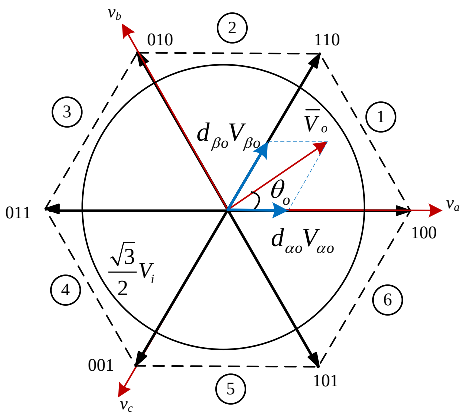



Figure 3. Switching strategy of the inverter switches

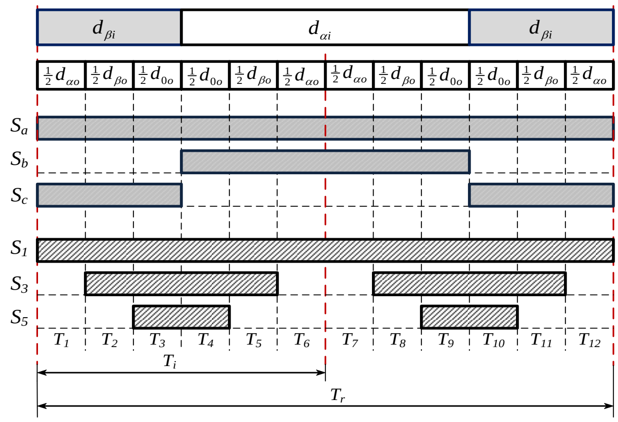



Figure 4. The switching coordination between the rectifier switches with the inverter for sector 1

To balance the input currents and the output voltages of the USMC, the switching of the rectifier stage must be coordinated with the switching of the inverter stage. The status change of the rectifier switches always occurs during the free-wheeling condition of the inverter switches [4-5]. The coordination strategy between the rectifier switches with the inverter switches is designed based method in [5]. Figure 4 shows the coordination between the rectifier switches with the inverter switches for sector 1. Figure 4 shows that each switching period of the rectifier switches Tr, there are two switching period of the inverter switches Ti, and then one switching period of the rectifier switches divided into 12 switching times with the following equation.

$$
\begin{aligned}
&T_1 = T_{12} = 0.5\ d_{\beta i}\ d_{\alpha o} \\
&T_2 = T_{11} = 0.5\ d_{\beta i}\ d_{\beta o} \\
&T_3 = T_{10} = 0.5\ d_{\beta i}\ d_{0o} \\
&T_4 = T_9 = 0.5\ d_{\alpha i}\ d_{0o} \\
&T_5 = T_8 = 0.5\ d_{\alpha i}\ d_{\beta o} \\
&T_6 = T_7 = 0.5\ d_{\alpha i}\ d_{0o} \\
&T_r = T_1 + T_2 + ... + T_{12} = 1
\end{aligned} \tag{9}
$$

The modulation pulses for switching the converter switches are achieved by compare the switching time in (9) with linear carrier pulse.

### 2.3 Direct Torque Control Strategy

According to the USMC modulation strategy using SVM method, direct torque control (DTC) based on space vector modulation (SVM) is proposed for variable speed control of PMSM. In this method, the stator flux linkage and electromagnetic torque are regulated to obtain the reference voltages for modulation of the USMC switches. Both the stator flux linkage and the electromagnetic torque are regulated by using PI controller, as shown in Figure 1. The dq-axis reference voltages for modulation the USMC switches can be written as :

$$
\begin{aligned}
v_{od}^* &= \left(K_p + \frac{K_i}{s}\right)\left(\psi_s^* - \psi_s\right) \\
v_{oq}^* &= \left(K_p + \frac{K_i}{s}\right)\left(T_e^* - T_e\right)
\end{aligned} \tag{10}
$$

Kp and Ki are the gain of PI controller. The estimated electromagnetic torque Te is obtained from (4) and the reference of stator flux linkage $\psi_s^*$ is assumed equal to the flux linkage of permanent magnet $\psi_f$. Based on (2), the estimated stator flux linkage $\psi_s$ and the estimated rotor position $\theta_\psi$ can be calculated by :

$$
\psi_s = \sqrt{\psi_d^2 + \psi_q^2} \quad \text{and} \quad \theta_\psi = \tan^{-1}\frac{\psi_q}{\psi_d} \tag{11}
$$

The reference of electromagnetic torque is obtained by regulating the rotor speed using PI controller, which is formulated by :

$$
T_e^* = \left(K_p + \frac{K_i}{s}\right)\left(\omega_m^* - \omega_m\right) \tag{12}
$$

Based on (10) and (11), the αβ-axis output voltages for reference the SVM in activating the inverter switches can be calculated by :

$$
\begin{bmatrix} v_{o\alpha}^* \\ v_{o\beta}^* \end{bmatrix} = \begin{bmatrix} \cos\left(\theta_\psi\right) & -\sin\left(\theta_\psi\right) \\ \sin\left(\theta_\psi\right) & \cos\left(\theta_\psi\right) \end{bmatrix} \begin{bmatrix} v_{od}^* \\ v_{oq}^* \end{bmatrix} \tag{13}
$$

Then, USMC will adjust the PMSM stator voltage through the inverter stage according to the reference voltage in (13) for rotor speed control, so that the rotor will rotate according to the required reference speed

## 3. SIMULATION RESULTS

The proposed SVM-based DTC for variable speed control of PMSM using USMC in Figure 1 is verified by simulation with parameters are listed in appendix. The proposed model is simulated with varying rotor speed and load torque under motoring mode and generating mode. The reference rotor speed is made to vary 300 rpm at initial conditions, then rises to 500 rpm in 1 second and drops to 400 rpm at 1.8 seconds, as shown in Figure 5. In motoring mode, load torque of PMSM varies from 5 Nm at starting conditions, then rises to 10 Nm at 7.5 seconds. At 1.5 seconds, PMSM operates in a generator mode with load torque -10 Nm, as shown in Figure 6.

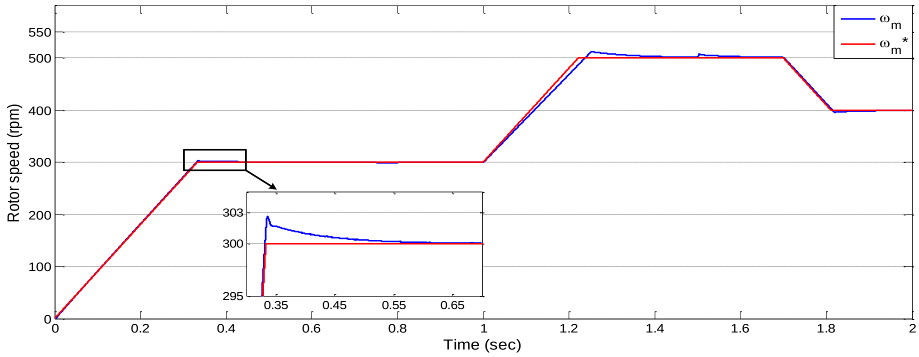



Figure 5. Rotor speed response

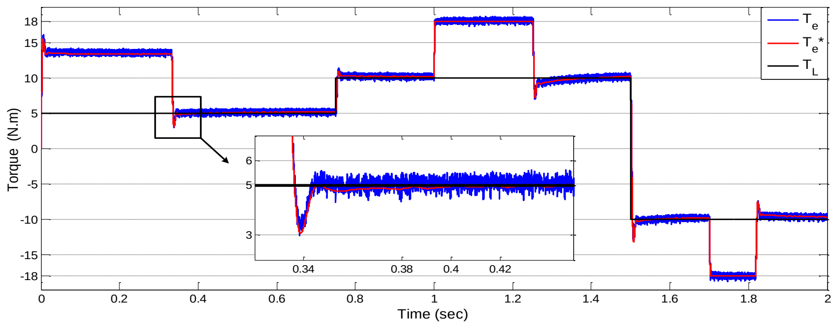



Figure 6. Torque response

Figure 5 shows that the rotor speed can follow the reference value for acceleration conditions as well as for the deceleration conditions with maximum error 9.3 rpm at transient conditions. This shows that the design of SVM-based DTC using USMC has been able to control the rotor speed of PMSM according to the reference speed. Figure 5 also shows that the rotor speed of PMSM also has a smooth ripple. This shows that the use of SVM method to modulate USMC switches produce a finer speed ripple than the hysteresis control method based on switching tables that exist in conventional DTC. This is an advantage of DTC-based SVM compared to conventional DTCs that use switching tables. The reliability of the SVM-based DTC can also be seen from the torque response, as shown in Figure 6. The electromagnetic torque of the PMSM can be regulated at the reference value obtained from the speed controller. This makes the rpm speed of PMSM can be controlled at reference speed, in accordance with DTC principle that control speed with direct torque arrangement. Figure 6 also shows that the proposed model has provided a smooth electromagnetic torque response. This is in accordance with the characteristics of SVM-based DTC, which has a smoother torque response than the conventional DTC. SVM-based DTC excess can also be seen from the stator flux linkage response, as shown in Figure 7. The magnitude of the stator flux linkage remains constant according to the flux linkage of the permanent magnet, as shown in Figure 7(a). This shows that the SVM-based DTC design has also successfully regulated the linkage flux according to the reference value, ie the flux linkage of the permanent magnet. In addition, the stator flux linkage also has a smooth response, as shown by the flux linkage locus circle in Figure 7(b). This shows that the SVM method has been able to improve the performance of DTC to regulate the electromagnetic torque and the flux linkage of PMSM.

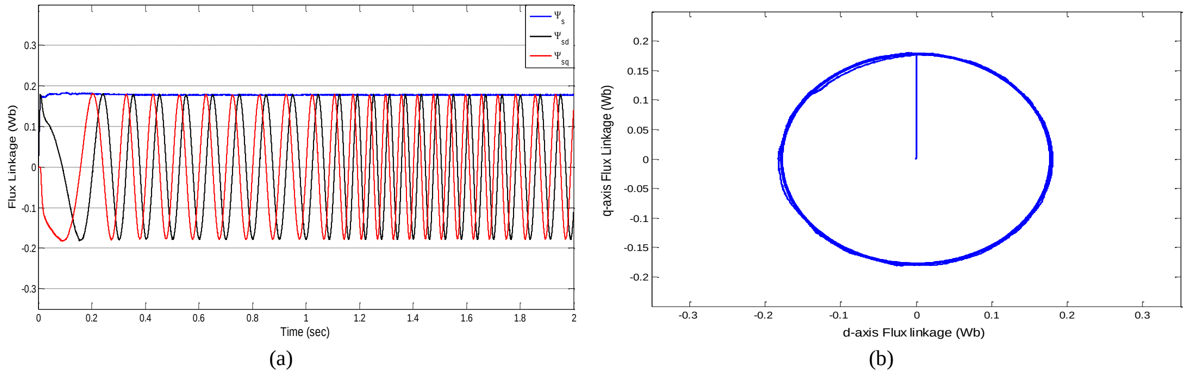



Figure 7. (a) The magnitude of the stator flux linkage, (b) Flux linkage locus circle

The reliability of SVM-based DTC in controlling PMSM speed is inseparable from the good performance of USMC. USMC can work as planned, as shown by Figure 8. Modulation strategy of the rectifier switches to generate maximum dc-link voltage has been obtained. Figure 8(a) shows the dc link voltage response corresponding to the maximum value of the input voltage. Since the zero vector of input current is eliminated to minimize switching losses, the dc link voltage does not exist at a zero value. Modulation strategies of rectifier switches are also designed to hold unity power factor at the input side. This goal has been reached, where the phase angle between the input voltage and the input current remains at zero, so that the power factor becomes unity. It can be seen from the graph of the input current and the input voltage in Figure 8(b).

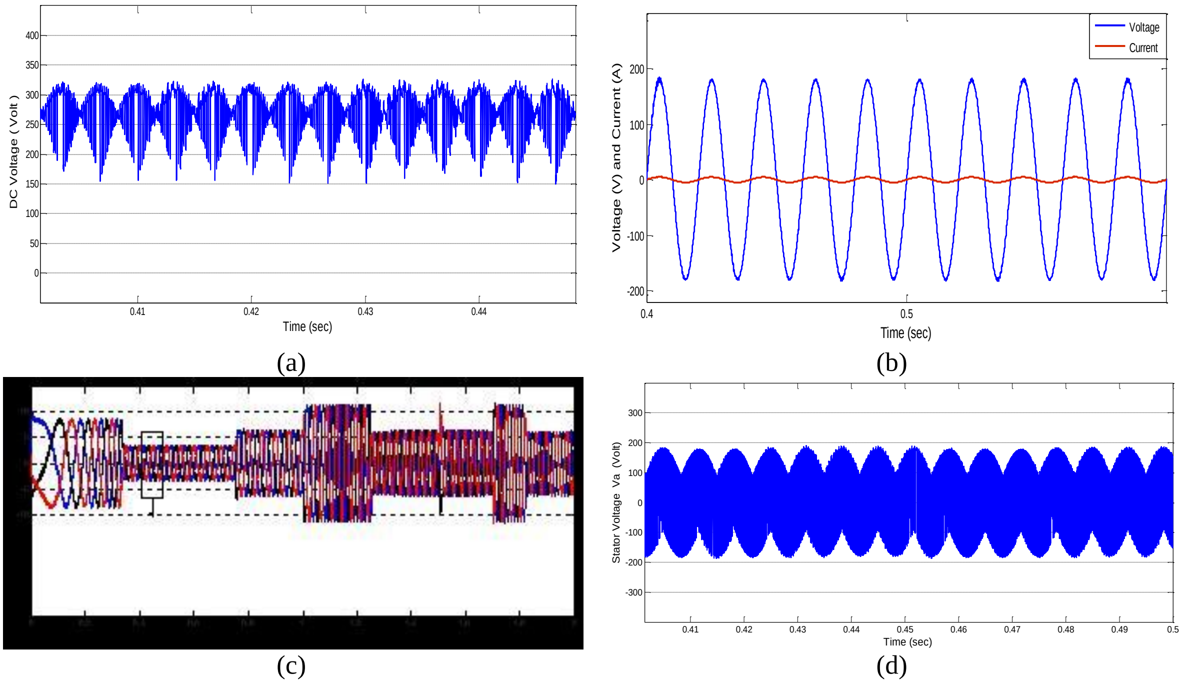



Figure 8. Performances of a USMC, (a) The dc link voltage, (b) the input current and voltage, (b) stator current, (d) stator voltage

One of the advantages of matrix converter is that it can generate sinuasoidal input and output waveforms. This makes the power quality of the matrix converter better than the back to back converter. It has also been obtained from USMC, as indicated by the waves of the input current and the input voltage in Figure 8(b) and the waves of the output voltage and the output current in Figure 8(c) and 8(d). This shows that the performance of USMC is the same as the conventional matrix converter, but the USMC advantage is that it has fewer active switches, so the manufacturing cost becomes cheaper. The performances of USMC in Figure 8 indicates that the purpose of using USMC to improve the power quality of the PMSM driver has been achieved. It is characterized by the acquisition of unity power factor on the input side and sinuasoidal input and output waveforms.

## 4. CONCLUSION

The proposed variable speed control of PMSM using SVM-based DTC by employing USMC has been discussed. In this method, the PMSM speed is adjusted by regulating the electromagnetic torque and the flux linkage of stator using PI controller. The advantages of this proposed method are to produce a finer electromagnetic torque response than the conventional DTC based table switching methods. The simulation results show that the proposed system has been able to control the electromagnetic torka and flux linkage according to the reference value with a smooth response, so that the PMSM speed operates according to the reference value with a smooth response as well. This shows that the purpose of using SVM based DTC to improve the performance of conventional DTC based switching tables has been achieved. USMC usage has also been able to improve the power quality of PMSM drivers by obtaining unity power factor on the input side and sinuasoidal input and output waveforms.

## APPENDIX

The parameter of PMSM are : Flux linkage of permanent magnet ψf = 0.175 Wb, number of pole pair p = 4, stator resistanceRs = 0.2 Ω, dq-axis of stator inductance Ld = Lq= 8.5 mH, momen of inertia J = 0.089 kgm2, friction coefficient B = 0.005 N.m.s/rad.
Power supply : 220 Volt 50 Hz.

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