Loss Minimization Strategy under Direct Torque Control Method Using Matrix Converter Fed IPMS Motor

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Abstract: *This paper develops a direct torque control method (DTC) using a matrix converter (MC) fed interior permanent magnet synchronous (IPMS) motor in loss minimization strategy. The nature of the system necessitates that the stator flux linkage amplitude is employed as the loss minimization control variable. Thus, the optimal stator flux linkage is determined in a way that the total electrical loss is minimized. Then the optimal flux is considered as the reference flux. The advantages of matrix converters are combined with the advantages of the loss minimization strategy; under the unrestrained of the rotor speed, the required voltage vectors are generated to implement the conventional DTC method of IPMS motor. The proposed DTC algorithm is applied to IPMS motors and the experimental results are given in steady-state and transient conditions, while the discussion about the trend of the DTC method using the MC is also carried out.*

Key words: *Loss minimization strategy, matrix converter, direct torque control method, IPMS motor, unlimited rotor speed control.*

1. Introduction

In the past two decades, due to the need to increase the quality and the efficiency of power supply and usage, the three phase matrix converter has become a major modern energy converter and has emerged from the previously conventional energy conversion modules as one of the best substitutions. It fulfills all the requirements of the conventionally used rectifier/DC-link/ inverter structures. Some advantages of the matrix converter can be seen as follows: the use of a compact voltage source, providing sinusoidal voltage with varying amplitude and frequency besides the sinusoidal input current and unity input power factor at the power supply side. As shown in Figure 1, a matrix converter has a simple topology and a compact design due to the lack of DC-link capacitor for energy storage. One of The best of advantages of the matrix convertor is to apply them for unlimited rotor speed control [1]. This subject is very important for implementation of loss minimization strategy. There are two powerful driving forces for energy saving practices i.e. the scarcity of primary energy resources and the ecological pollution crisis. Since most generated electricity is consumed by electric motors, their loss minimization has attracted much attention recently. Although interior permanent magnet synchronous (IPMS) motors are inherently efficient, their optimum efficiency is highly reliant on their control strategy. Generally, there exist two control strategies for providing loss minimization of electrical machines i.e. online and offline strategies [2]. In an online strategy, via a search procedure, a control variable change continuously or step-wise so that the minimum input power to the motor is reached. Such a strategy is insensitive to machine parameters and minimizes the total loss of both the machine and the drive. However, it is slow; because the search period must be carried out in the steady state. Thus, in applications experiencing repetitive transient states, it may not result in considerable energy savings. In the offline strategy, based on the machine model and operating conditions, first a loss function is calculated offline. A minimization of the function then results in an optimum control signal which is applied to the machine as a command. A loss minimization strategy can be integrated into any machine control method including vector control (VC) and direct torque control (DTC). Compared to VC method, the DTC method enjoys such advantages as lower dependency on machine parameters, faster dynamic response and less number of controllers. Many professionals have studied loss minimization of vector controlled IPMS motors; while only a few researchers have paid attention to the loss minimization of direct torque controlled motors. Reason of combination of the advantage of matrix convertor and disadvantage of loss minimization strategy is presented this paper [3].

2. DTC Principles by matrix converter

The three-phase matrix converter module includes nine bi-directional switches as shown in Figure 1. There are 27 switching configuration states, which mean 27 possible space vectors can be used to control IPMSM and can be split respectively into 3 groups as shown in Table 1; in Group I, two output lines are connected to one of the other input lines; in Group II, all output lines are connected to a common input line; while in Group III, each output line is connected to a different input line.

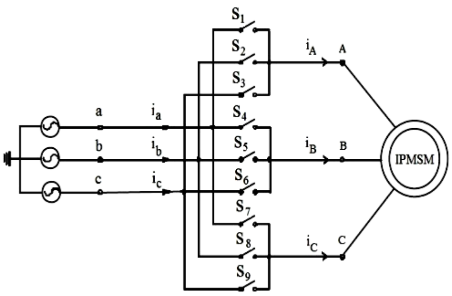

Fig.1 Schematic circuit of the simplified matrix converter drive

The corresponding output line-to-neutral voltage vector and input line current vector have fixed directions as represented in Figure 2. However, Group III is not useful. Only 18 non-zero space vectors in Group I (±1, ±2, …, ±9) and 3 zero space vectors in Group II (0a, 0b, 0c) can be usually employed in the modern control techniques for the matrix converter (such as the Space Vector Modulation, DTC methods, etc.) [4].

According to [4], the basic DTC principles using matrix converters can be briefly described as follows: at each sampling period, the proper switching configuration, which allows the compensation of instantaneous errors in the stator flux magnitude and torque, is selected under the constraint of unity input power factor. This last requirement of the input side of the matrix converter is intrinsically satisfied if the average value of sin (ψ_i) is maintained close to zero, where ψ_i is the displacement angle between the input line voltage and input line current. The average value of sin (ψ_i) is controlled close to zero because the input power factor is aimed close to unity. As a facultative example, after calculation at the first time of each sampling period and considering the stator flux vector lying in sector 1, the input voltage vector lying in sector 2, the output of the torque hysteresis comparator, the flux hysteresis comparator and the hysteresis comparator of the average value of sin (ψ_i) are respectively $c_T = +1$, $c_\phi = 0$ and $c_\psi = +1$. As shown in Figure 3, first with $c_T = +1$, $c_\phi = 0$ and the stator flux in sector 1, the suitable voltage vector $V_{6\text{-}vsi}$ is the VSI output voltage vector by the DTC algorithm in a given switching period from conventional switching Table of DTC.

TABLE I

Possible Switching Configurations of matrix convertor

Gr.	Vector	A	B	C	Vs	α_0	i_i	β_i
I	$+1_{MC}$	a	b	b	$2/3V_{ab}$	0	$2/\sqrt{3}\, i_{sa}$	$-\pi/6$
	-1_{MC}	b	a	a	$-2/3V_{ab}$	0	$-2/\sqrt{3}\, i_{sa}$	$-\pi/6$
	$+2_{MC}$	b	c	c	$2/3V_{bc}$	0	$2/\sqrt{3}\, i_{sa}$	$\pi/2$
	-2_{MC}	c	b	b	$-2/3V_{bc}$	0	$-2/\sqrt{3}\, i_{sa}$	$\pi/2$
	$+3_{MC}$	c	a	a	$2/3V_{ca}$	0	$2/\sqrt{3}\, i_{sa}$	$7\pi/6$
	-3_{MC}	a	c	c	$-2/3V_{ca}$	0	$-2/\sqrt{3}\, i_{sa}$	$7\pi/6$
	$+4_{MC}$	b	a	b	$2/3V_{ab}$	$2\pi/3$	$2/\sqrt{3}\, i_{sb}$	$-\pi/6$
	-4_{MC}	a	b	a	$-2/3V_{ab}$	$2\pi/3$	$-2/\sqrt{3}\, i_{sb}$	$-\pi/6$
	$+5_{MC}$	c	b	c	$2/3V_{bc}$	$2\pi/3$	$2/\sqrt{3}\, i_{sb}$	$\pi/2$
	-5_{MC}	b	c	b	$-2/3V_{bc}$	$2\pi/3$	$-2/\sqrt{3}\, i_{sb}$	$\pi/2$
	$+6_{MC}$	a	c	a	$2/3V_{ca}$	$2\pi/3$	$2/\sqrt{3}\, i_{sb}$	$7\pi/6$
	-6_{MC}	c	a	c	$-2/3V_{ca}$	$2\pi/3$	$-2/\sqrt{3}\, i_{sb}$	$7\pi/6$
	$+7_{MC}$	b	b	a	$2/3V_{ab}$	$4\pi/3$	$2/\sqrt{3}\, i_{sc}$	$-\pi/6$
	-7_{MC}	a	a	b	$-2/3V_{ab}$	$4\pi/3$	$-2/\sqrt{3}\, i_{sc}$	$-\pi/6$
	$+8_{MC}$	c	c	b	$2/3V_{bc}$	$4\pi/3$	$2/\sqrt{3}\, i_{sc}$	$\pi/2$
	-8_{MC}	b	b	c	$-2/3V_{bc}$	$4\pi/3$	$-2/\sqrt{3}\, i_{sc}$	$\pi/2$
	$+9_{MC}$	a	a	c	$2/3V_{ca}$	$4\pi/3$	$2/\sqrt{3}\, i_{sc}$	$7\pi/6$
	-9_{MC}	c	c	a	$-2/3V_{ca}$	$4\pi/3$	$-2/\sqrt{3}\, i_{sc}$	$7\pi/6$
II	0_a	a	a	a	0	-	0	-
	0_b	b	b	b	0	-	0	-
	0_c	c	c	c	0	-	0	-
III	x	a	b	c	x	x	x	x
	x	a	c	b	x	x	x	x
	x	b	c	a	x	x	x	x
	x	b	a	c	x	x	x	x
	x	c	a	b	x	x	x	x
	x	c	b	a	x	x	x	x

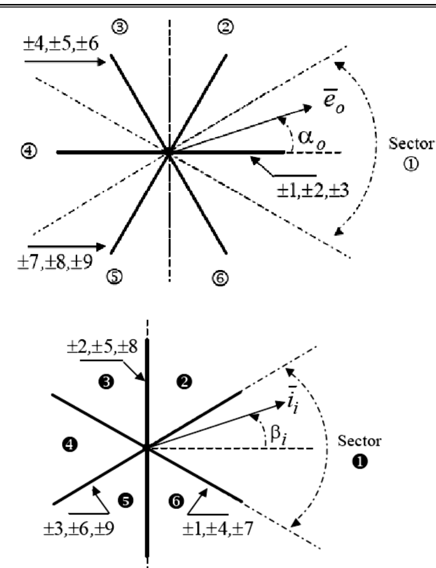

Fig. 2 (a) The output line-to-neutral voltage vectors, (b) The input line current vectors

TABLE II
Matrix Converter Switching Table for DTC control

Sector of $\vec{v}_i$	1		2		3		4		5		6	
c_φ	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
$V_{1\text{-}VSI}$	-3-_{MC}	$+1\text{-}_{MC}$	$+2\text{-}_{MC}$	-3-_{MC}	-1-_{MC}	$+2\text{-}_{MC}$	$+3\text{-}_{MC}$	-1-_{MC}	-2-_{MC}	$+3\text{-}_{MC}$	$+1\text{-}_{MC}$	-2-_{MC}
$V_{2\text{-}VSI}$	$+9\text{-}_{MC}$	-7-_{MC}	-8-_{MC}	$+9\text{-}_{MC}$	$+7\text{-}_{MC}$	-8-_{MC}	-9-_{MC}	$+7\text{-}_{MC}$	$+8\text{-}_{MC}$	-9-_{MC}	-7-_{MC}	$+8\text{-}_{MC}$
$V_{3\text{-}VSI}$	-6-_{MC}	$+4\text{-}_{MC}$	$+5\text{-}_{MC}$	-6-_{MC}	-4-_{MC}	$+5\text{-}_{MC}$	$+6\text{-}_{MC}$	-4-_{MC}	-5-_{MC}	$+6\text{-}_{MC}$	$+4\text{-}_{MC}$	-5-_{MC}
$V_{4\text{-}VSI}$	$+3\text{-}_{MC}$	-1-_{MC}	-2-_{MC}	$+3\text{-}_{MC}$	$+1\text{-}_{MC}$	-2-_{MC}	-3-_{MC}	$+1\text{-}_{MC}$	$+2\text{-}_{MC}$	-3-_{MC}	-1-_{MC}	$+2\text{-}_{MC}$
$V_{5\text{-}VSI}$	-9-_{MC}	$+7\text{-}_{MC}$	$+8\text{-}_{MC}$	-9-_{MC}	-7-_{MC}	$+8\text{-}_{MC}$	$+9\text{-}_{MC}$	-7-_{MC}	-8-_{MC}	$+9\text{-}_{MC}$	$+7\text{-}_{MC}$	-8-_{MC}
$V_{6\text{-}VSI}$	$+6\text{-}_{MC}$	-4-_{MC}	-5-_{MC}	$+6\text{-}_{MC}$	$+4\text{-}_{MC}$	-5-_{MC}	-6-_{MC}	$+4\text{-}_{MC}$	$+5\text{-}_{MC}$	-6-_{MC}	-4-_{MC}	$+5\text{-}_{MC}$

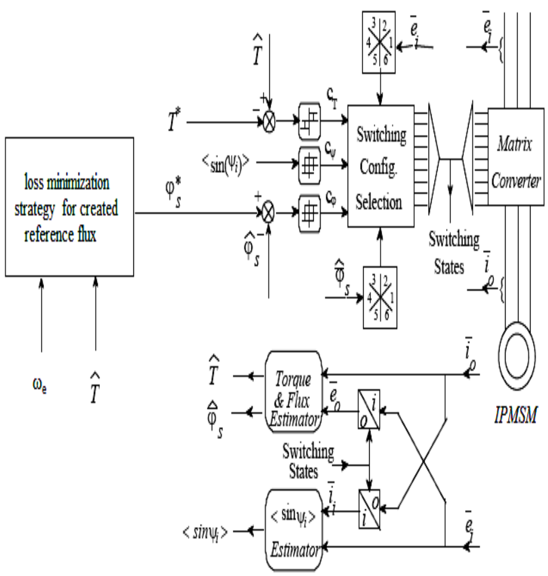

Fig.3 Block diagram of the proposed DTC scheme for matrix converter.

Then, with the chosen VSI voltage vector $V_{6\text{-vsi}}$, $c_\psi = +1$ and the input voltage vector in sector 2, the opportune matrix converter voltage vector is finally selected as V_{-5MC} from Table 2. The schematic of the DTC method using the matrix converter fed IPMS motor is represented in Figure 3. The reference values of the torque and the stator flux are compared with the estimated values and coordinate with the average value of the sin (ψ_i) hysteresis comparator. In the lower part of the block diagram, the estimators of the electromagnetic torque, stator flux and the average value of sin (ψ_i) are represented. These estimators require the knowledge of input and output of voltages and currents for the matrix converter. However, only the input voltages and the output currents of the matrix converter module are measured by sensors, while other quantities such as the input voltages of the IPMS motor and the input currents of the matrix converter module are calculated from the previous switching states, the input voltages and the output currents of the matrix converter module [5].

3. Machine Model

Electrical loss in electric machines mainly consists of copper loss as well as iron loss. In order to minimize the loss of IPMSM, a machine model incorporating these losses is needed. A steady state model of IPMSM in a d-q reference frame is shown in Fig. 4. Here, R_s and R_c stand for copper and iron loss resistances, respectively. If ψ_s is the stator flux linkage, ψ_d and ψ_q are its d- and q-axis components, and δ is load angle or the angle between the stator linkage flux and permanent magnet flux. Then, according to Fig. 5, it can be written [6],[7]:

$$\psi_d=\psi_m+L_s i_{do} \quad , \quad \psi_q=L_s i_{qo} \tag{1}$$

$$\psi_d=\psi_s\cos\delta \quad , \quad \psi_q=\psi_s\sin\delta \tag{2}$$

Also, the electromagnetic torque as a function of stator flux and load angle would be as follows:

$$T_e=\frac{3P\psi_s\psi_m}{2L_s}\sin\delta \tag{3}$$

The motor drive dynamics is also represented by:

$$T_e-T_l=B\omega+J\frac{d\omega}{dt} \tag{4}$$

Where the T_L is load torque. In the steady state we have $\frac{d\omega}{dt}=0$ therefore:

$$T_e=T_l+B\omega \tag{5}$$

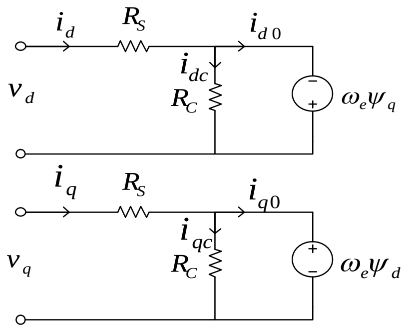

Fig.4 A steady state model for IPMSM machines

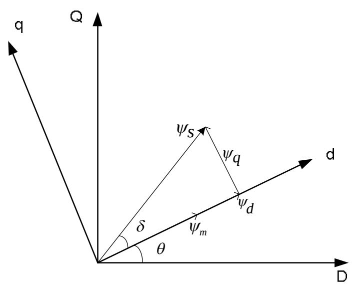

Fig. 5 Vector diagram

4. Steady State Electrical Loss

In DTC, calculations are carried out in a stationary reference frame. Measuring the machine currents, the stator linkage flux and the electromagnetic torque are estimated. Thus, the nature of DTC method dictates the stator flux amplitude to be the only control variable for handling the electrical loss. Hence, here, the electrical loss function is directly derived as a function of stator linkage flux. Considering Fig.4, the steady state electrical loss function and its components, the output power and efficiency can be expressed as [8]-[14]:

$$P_{loss}=P_{cu}+P_{fe} \tag{6}$$

$$P_{fe}=\frac{3}{2}R_c\left(i_{dc}^2+i_{qc}^2\right) \tag{7}$$

$$P_{cu}=\frac{3}{2}R_s\left(i_d^2+i_q^2\right) \tag{8}$$

$$P_{out}=T_l\omega_m \tag{9}$$

$$\eta=\frac{P_{out}}{P_{out}+P_{loss}} \tag{10}$$

Using (3) we have:

$$\sin\delta=\frac{2L_sT}{3P\psi_s\psi_m} \quad , \quad \cos\delta=\sqrt{1-\left(\frac{2L_sT}{3P\psi_s\psi_m}\right)^2} \tag{11}$$

From Fig.4, in the steady state and with considering of (1) and (2), we also have:[15],[16].

$$i_d=i_{d0}+i_{dc} \quad , \quad i_q=i_{q0}+i_{qc} \tag{12}$$

$$i_{dc}=-\frac{\omega_e\psi_q}{R_c}=-\frac{\omega_e\psi_s\sin\delta}{R_c} \tag{13}$$

$$i_{qc}=\frac{\omega_e\psi_d}{R_c}=\frac{\omega_e\psi_s\cos\delta}{R_c} \tag{14}$$

$$i_{d0}=\frac{\psi_d-\psi_m}{L_s}=\frac{\psi_s\cos\delta-\psi_m}{L_s} \tag{15}$$

$$i_{q0}=\frac{\psi_q}{L_s}=\frac{\psi_s\sin\delta}{L_s} \tag{16}$$

Substituting (13)–(14) into (7) gives iron loss as:

$$P_{fe}=\frac{3}{2}\frac{(\omega_e\psi_d)^2+(\omega_e\psi_q)^2}{R_c}=\frac{3}{2}\frac{(\omega_e\psi_s)^2}{R_c} \tag{17}$$

Also Substituting (13)–(16) into (12) gives id and iq. Inserting these currents into (8), along with some mathematical simplification, copper loss is derived as:

$$P_{cu}=3/2\left(\left(\frac{R_s}{L_s^2}+\frac{R_s\omega_e^2}{R_c^2}\right)\psi_s^2+\left(\frac{4T_e\omega_eR_s}{3PR_c}+\frac{R_s\psi_m^2}{L_s^2}\right)-2\frac{\psi_mR_s}{L_s^2}\sqrt{\psi_s^2-\left(\frac{2T_eL_s}{3P\psi_m}\right)^2}\right) \tag{18}$$

Therefore the loss function is obtained as:

$$P_{loss}=3/2\left(\left(\frac{\omega_e^2}{R_c}+\frac{R_s}{L_s^2}+\frac{R_s\omega_e^2}{R_c^2}\right)\psi_s^2+\left(\frac{4T_e\omega_eR_s}{3PR_c}+\frac{R_s\psi_m^2}{L_s^2}\right)-2\frac{\psi_mR_s}{L_s^2}\sqrt{\psi_s^2-\left(\frac{2T_eL_s}{3P\psi_m}\right)^2}\right) \tag{19}$$

Equation (19) expresses the steady state electrical losses as a function of stator flux amplitude. Therefore, for a given T_e and ω_e in the magnetic flux plane, the circle $|\psi_s|$=constant gives the locus of constant electrical losses. For a given operational condition, Fig. 6 demonstrates the electrical losses as a function of stator flux amplitude variations [17]-[23].

5. The Proposed Loss Minimization Method

From (19), the derivative of steady state loss as a function of stator flux variation will be as follows:

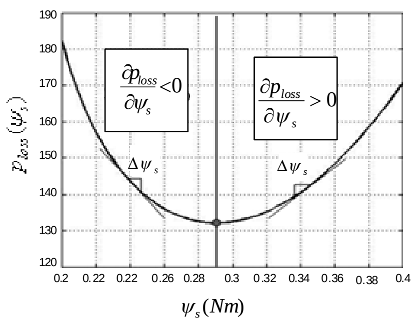

Fig. 6: Electrical loss curve versus flux amplitude

$$\frac{\partial P_{loss}}{\partial \psi_s}=A\psi_s+\frac{B}{\sqrt{1-(\frac{C}{\psi_s})^2}} \tag{20}$$

Where

$$A=\frac{3\omega_e^2}{R_c}+\frac{3R_s}{L_s^2}+\frac{3R_s\omega_e^2}{R_c^2}$$

$$B=-3\frac{R_s\psi_m}{L_s^2} \quad , \quad C=\frac{2L_sT_e}{3P\psi_m} \tag{21}$$

When the stator flux variation, $\Delta\psi_s$, is small enough, we'll have:

$$P_{loss}(\psi_s+\Delta\psi_s)\simeq P_{loss}(\psi_s)+\frac{\partial P_{loss}}{\partial \psi_s}\Delta\psi_s \tag{22}$$

This equation is obtained by a first order expansion of Taylor series. Equation (22) shows the steady state electrical loss variation versus small variation of magnetic flux amplitude. A decreasing machine loss is obtained if the machine flux changes in a way so that the second term in the right side of (22) becomes negative. Therefore, to reduce the machine's electrical loss, first, the loss function derivative with respect to stator flux amplitude variation should be calculated. If this derivative is positive, then, the stator flux amplitude should be decreased, while, if it is negative, the stator flux amplitude should be increased (shown in Fig.6). Since the loss function includes only one minimum, (Fig.6), thus, the repetitive application of the mentioned rule will give the optimum magnetic flux, and in turn, the minimum electrical loss. Since, in DTC, flux and torque controls are done independently, after some times, both torque and in turn, reference speed and the minimum loss will be achieved. For example, if the vector is located in the first zone, the voltage vectors V2 and V3 increase the torque, while V5 and V6 decrease it . Now, if electromagnetic torque becomes less than the reference torque, then, one of the voltage vectors V2 or V3 should be applied to machine, where V2 increases and V3 decreases the stator flux amplitude, respectively. In the proposed method, if derivative of the loss function is positive, V3 will be chosen and if it is negative, V2 would be the choice. Therefore, in each sampling time, our loss minimization algorithm will be as follows:

a. Measure the currents, voltages and speed of the machine.

b. Estimate the instantaneous stator flux and electromagnetic torque.

c. Choose the voltage vector that compensate for the torque error and cause less loss provided that the operating point is constant.

d. Apply this voltage for time Ts to the machine.

6. Implementation of the DTC Scheme and Laboratory Setup of the Drive System and Experimental Results

The proposed control strategy has been implemented on a 7 kVA matrix converter prototype feeding a standard three phase 1.1 kW, 4-pole, 380 V star connected, 50 Hz IPMS motor. A block diagram of the system is shown in Fig.7.

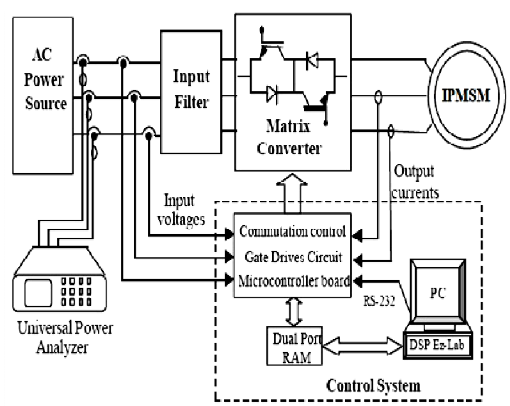

Fig.7 Block diagram of the laboratory Matrix-DTC drive system

The system setup is basically the one that has been used for the SVM modulation strategies tests. For this reason, in this section only details on different system settings with respect to that description will be given. The AC Power Source have been used to generate a balanced and sinusoidal three phase supply voltage system with a 310 V peak value for the line-to-neutral voltages. The line impedance was set to 0.5 Ω phase resistance and 200 μH phase inductance. The capacitance of the LC filter have been increased despite of the lower rated load power and set to 14.8 μF. This was done to reduce the input filter cut-off frequency. In addition, in order to damp oscillations, a 37Ω-7W resistor was applied in parallel to the filter inductances. With regard to the control system, it is worth noting that several modifications have been brought to the micro-controller program. With respect to the SVM control, the timing of the cycle period was modified. Moreover, the program was modified in order to apply to the motor just one matrix switching configuration per cycle period. The values of the reference control quantities were those quoted in the previous section for the numerical simulations: reference stator flux amplitude and electromagnetic torque equal to 0.644 Wb and 3.96 Nm respectively. The hysteresis band was ± 0.5% for the stator flux and ± 10% for the torque. Zero was the value for the reference $\sin(\varphi_i)$ as well as for its hysteresis band.

The sampling frequency was 12 kHz (≈ 83 μs cycle period). The motor was operated at 500 rpm approximately.

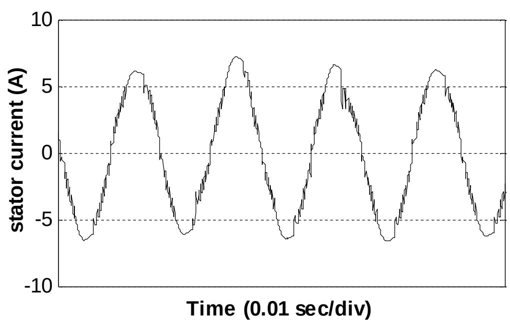

Fig.8 Stator current at 400 rad/s, 3.96 Nm with voltage source inverter

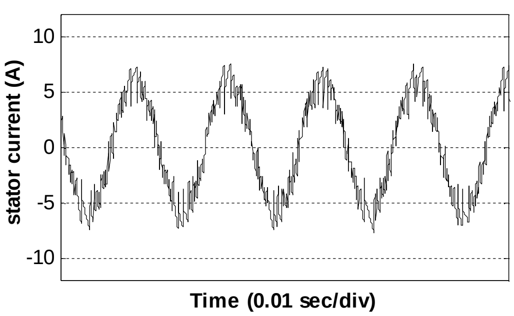

Fig.9 Stator current at 400 rad/s, 3.96 Nm with matrix converter

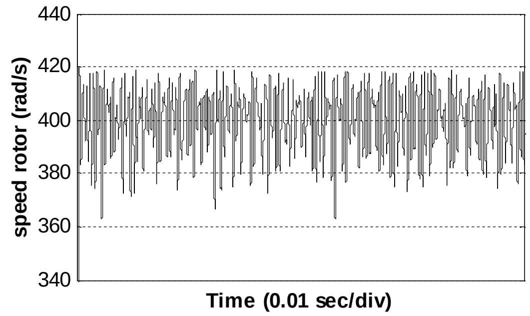

Fig.10 speed rotor at 3.96 Nm with voltage source inverter

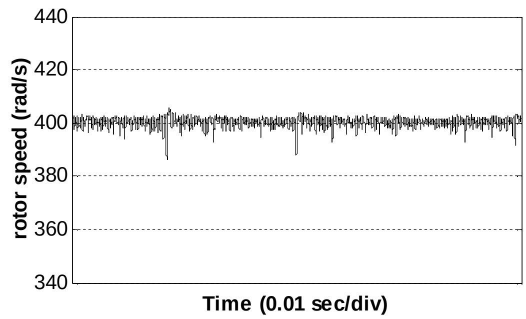

Fig.11 speed rotor at 3.96 Nm with matrix convertor

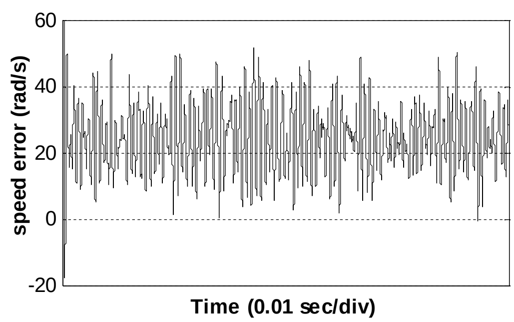

Fig.12 speed error at 430 rad/s and 3.96 Nm with voltage source inverter

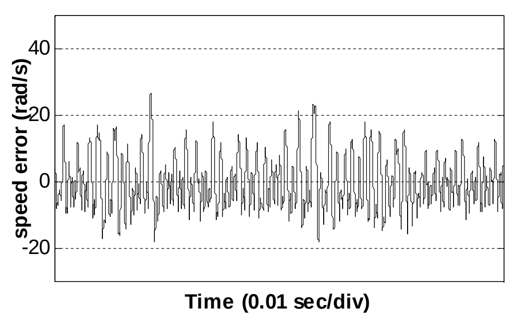

Fig.13 speed error at 430 rad/s and 3.96 Nm with matrix convertor

The current ripple in strategy of loss minimization that IPMS fed matrix converter is less than condition of motor fed VSI according to figures 8 and 9 respectively. In figures 10 and 11 rotor speed at 400 rad/s is shown that it is seen loss minimization strategy in high speed has very ripple. Figure 12 shows disadvantage of loss minimization strategy by voltage source inverter. In this conditions reference speed is 430 rad/s but speed error with voltage source inverter not zero according to fig.12. In fact rotor cannot track the reference speed. Matrix converter is compensated this subject and it is seen that unlimited rotor speed control is accomplished via matrix converter.

7. Loss minimization strategy in comparison with other control strategies with matrix converter

Novel loss minimization methods are usually compared with the i_d=0 and maximum torque per ampere control strategy (MTPA). In the i_d=0 control strategy the d-axis flux is the same as the magnet flux and in the MTPA control strategy the iron loss is not considered and only copper loss is minimized. For the interior permanent magnet synchronous motors the amplitude of flux for i_d=0 control strategy and that of MTPA one are the same. Here the amplitude of stator flux linkage under the i_d=0 control strategy is calculated:

$$\psi_d=\psi_m \tag{23}$$

$$T_e=\frac{3P\psi_m}{2}i_q \longrightarrow i_q=\frac{2T_e}{3P\psi_m} \tag{24}$$

$$\psi_q=L_s i_q=\frac{2T_e L_s}{3P\psi_m} \tag{25}$$

$$\psi_s=\sqrt{\psi_d^{\,2}+\psi_q^{\,2}} \tag{26}$$

Substituting (24) and (25) into (26) gives ψ_s:

$$\psi_s=\sqrt{\psi_m^{\,2}+\left(\frac{2T_e L_s}{3P\psi_m}\right)^2} \tag{27}$$

In this study, the motor operates at nominal speed (ω_e=400 rad/s), while the load torque is varied from no load to nominal one (T_L=3.96 Nm). The motor loss and the motor efficiency versus load torque variations are depicted in Figs. 14 and 15, respectively. Here, for the i_d=0 and MTPA control strategies, the control method is a traditional DTC and hysteresis band of both flux and torque are considered to be 10 percent of their nominal values. In another study, it is assumed that the motor is operated at nominal conditions (ω_e=400 rad/s and T_L=3.96 Nm) under i_d=0 control strategy, then the loss minimization control strategy is started. In Fig.16 the loss index i.e. $\frac{\partial P_{loss}}{\partial \psi_s}$ is shown. In comparison with online loss minimization control strategies where, a step change in stator flux linkage of machine is applied in the steady state repeatedly, and the resulted change in the input power of the machine caused by variation in the stator flux is measured in search for an optimal flux corresponding to a minimum input power, here the effect of stator flux linkage variations on electrical-loss are foreseen from the static model of the machine before flux is changed. Also, the variations of the stator flux are small. Thus, the proposed loss minimization control method is very fast.

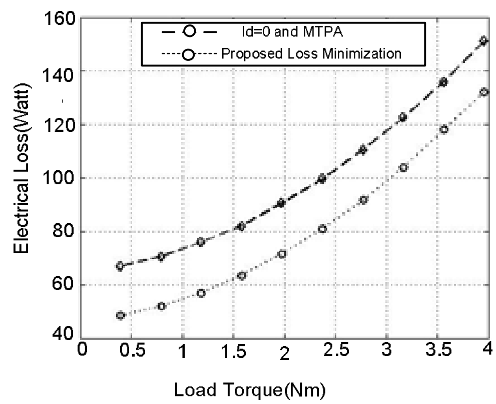

Fig.14 The comparison of the electrical loss under i_d=0 and MTPA control strategies and the proposed method

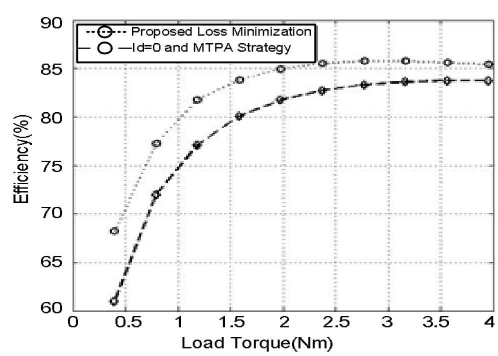

Fig.15: The comparison of the machine efficiency under i_d=0 control and MTPA control strategy and the proposed method

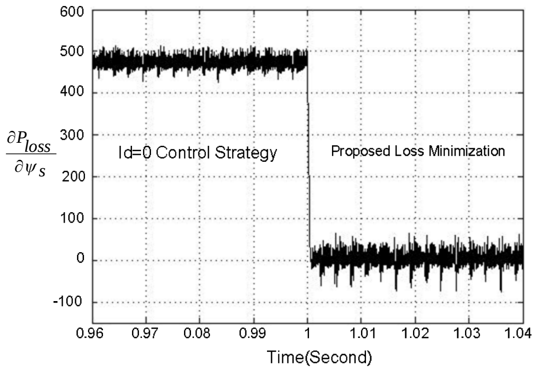

Fig.16: The loss index under i_d=0 strategy and the proposed method

On the other hand, it is different from offline or model based loss minimization control method where, the optimum value of flux is obtained from a minimum loss function through a derivation of the loss function and solving a complicated algebraic equation. Compared to this, here, the optimum value of the flux will be obtained using a simple constraint which is the negation of the loss function derivative that it survey with DTC method control and source of matrix convertor.

8. Conclusion

A new method was presented for the loss minimization direct torque controlled IPMSM with matrix converter. This method integrates a novel loss minimization control strategy with a modified DTC. First, the copper and iron losses were derived as a function of amplitude of the stator flux. Then, with a simple constraint, 18 voltage vectors are applied to the machine conducting the stator linkage flux towards the reduction of electrical loss via matrix converter. In order to illustrate the method, it was experimented on a typical IPMSM. The experimental results proved the significant role of the proposed method in improving the machine efficiency and reducing the electrical loss. One important result is take about of loss minimization strategy that it is performance at high speed. Loss minimization strategy cannot response to high reference speed rotor with voltage source inverter because at high speed effect of machine reactance more than effect of resistance. So matrix converter is compensated this subject and loss minimization strategy with MC is applied to unlimited rotor speed control.

Appendix

TABLE III
The Specification of the IPMSM

Nominal speed	400 Rad/s
λ_m	0.644 Wb
L_d	44.57mH
Lq	38.7mH
Nominal torque	3.96 Nm
Number of Poles	4
R_c	330 Ω
R_s	5.83 Ω
Friction Factor	0.0008

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