Application of the Matrix Converter for the Sensorless Position Control of Permanent Magnet AC Machines Using High Frequency Injection

D. Saltiveri[1], G. Asher[1], M. Sumner[1], A. Arias[2], L. Romeral[2]
[1]UNIVERSITY OF NOTTINGHAM
SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING
University Park, NG7 2RD Nottingham, England, UK
Tel: +44 / (115) – 9515549, Fax: +44 / (115) – 9515616
E-Mail: saltive@eel.upc.es, greg.asher@nottingham.ac.uk, mark.sumner@nottingham.ac.uk
URL: http://www.nottingham.ac.uk
[2]TECHNICAL UNIVERSITY OF CATALONIA
ELECTRONICS ENGINEERING DEPARTMENT
Colom 1, 08222 Terrassa, Catalonia, Spain
Tel: +34 / (93) – 7398015, Fax: +34 / (93) – 7398016
E-Mail: arias@eel.upc.es, romeral@eel.upc.es
URL: http://www.upc.com

Keywords

«Matrix converter», «Sensorless control», «Permanent magnet motor»

Abstract

This paper investigates the use of a Matrix Converter for the sensorless position control of a Surface Mounted Permanent Magnet Synchronous Machine using High Frequency injection. The Matrix Converter has almost zero dead time, which means that behaves almost like an ideal power converter and achieves better results than the conventional Voltage Source Inverter. A comparison of the sensorless technique proposed using both converters is made.

I. Introduction

Permanent Magnet Synchronous Motors (PMSM) have numerous advantages over induction machines, in particular higher efficiency, higher power density and better dynamic performance. To control a PMSM accurate knowledge of the rotor position is needed and usually PMSM drives use optical encoders for position measurement. This reduces the overall reliability and increases cost. For this reason, intensive research has been carried out in recent years to achieve sensorless control. Nevertheless, sensorless position control is still a challenge, especially for Surface Mounted Permanent Magnet Synchronous Machines (SMPMSM), where the magnet saliency is rather small. Among different sensorless techniques, the High Frequency (HF) voltage injection allows the tracking of even small magnet saliencies, assuring acceptable position estimations even at zero speed [1] [2] [3].

Other problems inherent to the AC Converters, which become apparent when using sensorless techniques, are the converter non-linearities, especially dead time and its consequent current clamping at zero current values [4] [5] [6]. Despite the fact that there are several methods to reduce or compensate such non-linearities, a novel promising method to overcome them is the replacement of the conventional Voltage Source Inverter (VSI) by a Matrix Converter (MC), which can be built with almost zero dead time and, therefore, its behaviour can be almost completely linear [7]. Promising achievements for sensorless speed control have already been reported in [8].

The paper is focused on sensorless position control by means of HF injection using a Matrix Converter and compares the same sensorless method using a VSI with dead time compensation. Experimental results demonstrate the superior performance of the Matrix Converter system.

II. High Frequency injection for sensorless position control

To detect rotor position using HF injection techniques a magnetic saliency is needed. A synchronous PM machine is said to be salient if the stator inductance measured in the direction of the flux L_d is different to the inductance measured in the direction of the torque producing axis L_q. Surface mounted PM machines are generally considered to have symmetrical rotors, but a small amount of geometrical asymmetry is normally present due to the semi-insertion of the magnets into the rotor iron. Saturation-induced saliency on the other hand is not fixed to the rotor and will be affected by the stator currents.

In a surface mounted PM with semi-inserted magnets, as shown in figure 1, the extra iron in the quadrature magnetic path q and the stator's teeth saturation in the flux direction d result in small saliency in the effective air gap length. As a result, the inductance in the flux axis L_d is smaller than the inductance in the quadrature axis L_q producing the stator inductance to be a function of the rotor position.

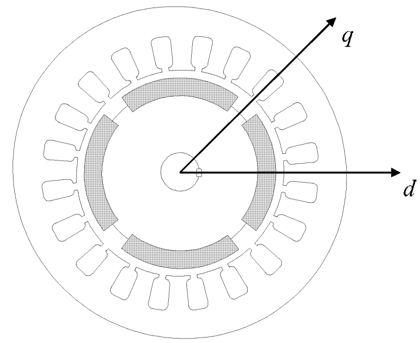

Fig. 1: Surface mounted PM machine with semi-inserted magnets

The α-β model of a synchronous PM machine in the stator reference frame including the saliency is given by equations (1) and (2).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_b \end{bmatrix} + \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} \cdot \begin{bmatrix} \psi_\alpha \\ \psi_\beta \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \psi_\alpha \\ \psi_\beta \end{bmatrix} = \begin{bmatrix} \overline{L}_s - \Delta L_s \cos(2\theta_r) & -\Delta L_s \sin(2\theta_r) \\ -\Delta L_s \sin(2\theta_r) & \overline{L}_s + \Delta L_s \cos(2\theta_r) \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \psi_m \begin{bmatrix} \cos(\theta_r) \\ \sin(\theta_r) \end{bmatrix} \tag{2}$$

where the stator inductance is defined as equation (3) shows

$$\overline{L}_s = \frac{L_q + L_d}{2} \tag{3}$$

and the saliency is given by equation (4)

$$\Delta L_s = \frac{L_q - L_d}{2} \tag{4}$$

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From equation (2), it can be seen that due to the saliency, the relation between the stator voltage and currents, or inductance matrix, is a function of the rotor position.

In order to extract the position information contained in the inductance matrix of equation (2), the HF rotating voltage vector given by equation (5) is added to the stator voltages [3].

$$v_i = \begin{bmatrix} v_{\alpha i} \\ v_{\beta i} \end{bmatrix} = \hat{V}_i \begin{bmatrix} -\sin(\omega_i t) \\ \cos(\omega_i t) \end{bmatrix} \tag{5}$$

If the injection frequency $\omega_i >> \omega_e$, where ω_e is the synchronous excitation frequency, the induced HF currents in the stator windings are given by equation (6).

$$i_i = \begin{bmatrix} i_{\alpha i} \\ i_{\beta i} \end{bmatrix} \approx \begin{bmatrix} I_0 \cos(\omega_i t) + I_1 \cos(2\theta_r - \omega_i t) \\ I_0 \sin(\omega_i t) + I_1 \sin(2\theta_r - \omega_i t) \end{bmatrix} \tag{6}$$

where I_0 and I_1 are as equations (7) and (8) indicate, respectively:

$$I_0 = \frac{\hat{V}_i \overline{L}_s}{L_d L_q \omega_i} \tag{7}$$

$$I_1 = \frac{\hat{V}_i \Delta L_s}{L_d L_q \omega_i} \tag{8}$$

In equation (6) it can be seen that only the negative sequence component, proportional to the saliency value, contains rotor position information. To extract this useful signal from the total high frequency current the Heterodyne Signal Processing [1] [2] [3], shown in figure 2, must be implemented.

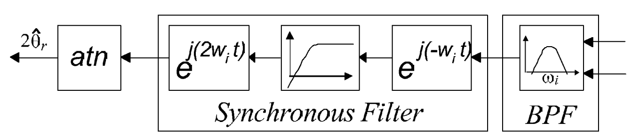


Fig. 2: Heterodyne Signal Processing for estimating the rotor angle position

The Band Pass Filter removes the fundamental component and leaves the HF component. The first rotation of coordinates transforms the HF currents to a rotating frame synchronous with the voltage injection, converting the positive sequence current into DC. Therefore, by means of a High Pass filter it can be completely removed. Finally, a rotation back attached to the frame synchronous with the negative sequence produces the position signals at base band, as given in equation (9). The angle $2\theta_r$ can be then extracted directly by an arc tangent (atn).

$$\begin{bmatrix} i_{\alpha\_pos} \\ i_{\beta\_pos} \end{bmatrix} \approx \begin{bmatrix} I_1 \cos(2\theta_r) \\ I_1 \sin(2\theta_r) \end{bmatrix} \tag{9}$$

Figure 3 shows the diagram of the SMPMSM sensorless position control where the HF voltage components alpha and beta are added to the reference voltages.

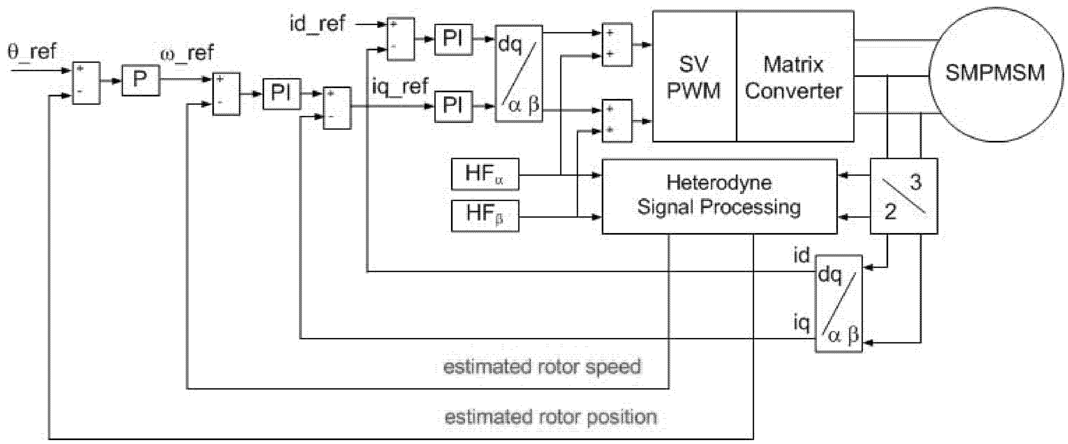


Fig. 3: Diagram for the sensorless position control of a SMPMSM using Matrix Converter

In a SMPMSM the saliency is small and not perfectly sinusoidal, which has two major effects for the application of the voltage injection strategy. First the level of useful position signal is small and the distortion in the HF currents due to the inverter's non-linearities i.e. dead time becomes significant. Second, the saliency is not sinusoidally distributed and furthermore its shape and phase shift with respect to the rotor position will be load dependent [9]. This will produce harmonics in the position signals in equation (9) and in turn will produce angle estimation errors.

III. Converter non-linearities on HF injection sensorless control

Converter non-linearities affect all power electronic motor drives, but they are especially influential in sensorless drives, both observer based and those using HF injection. The converter non-linear characteristics have a significant impact on sensorless control, in comparison with machine effects. The most important ones, especially when using such a sensorless technique, are dead time of the IGBT and zero current clamping. These non-linearities introduce a distortion on the HF currents and, therefore, in the final estimated rotor position. Several methods have been reported to compensate these non-linearities. However, none of them can completely overcome their effects.

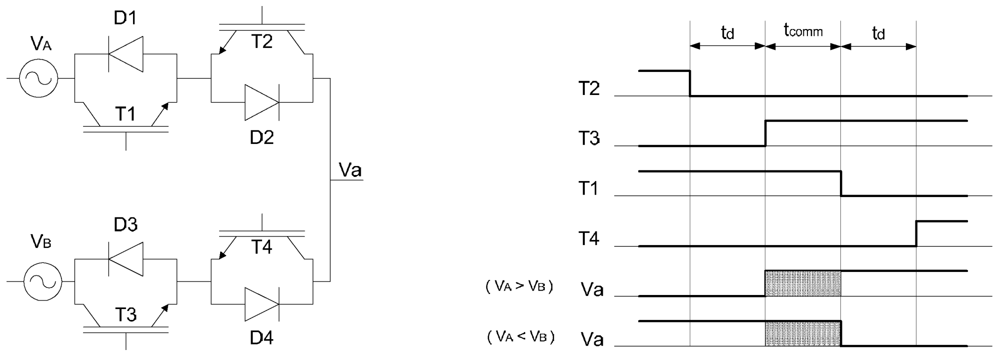
Voltage Source Inverter

In order to avoid short circuits on the DC side of the converter, a delay time between switching two devices in one converter leg is introduced. This delay time, commonly known as dead time, is known to cause significant distortion of the converter output current whenever the phase current changes its sign. The current distortion is caused by deviation of the output voltage from the demanded voltage. Although the voltage distortion due to dead time is relatively small it is significant when compared with the magnitude of the injected HF carrier signal. This voltage causes distortion of the fundamental current around zero crossing and also reduces the amplitude of the high frequency current. Moreover, with the high frequency carrier signal superimposed on to the fundamental voltage vector the stator currents are forced to multiple zero crossings when the fundamental phase currents are close to zero [10] [11]. Regardless of the current direction, the magnitude of the current always decreases toward zero during dead time. So if the magnitude of the current at the beginning of dead time is small enough to reach zero, after reaching zero the current remains zero until the end of dead time. This phenomenon, known as zero current clamping, occurs in each phase current when it is near zero and hence adds strong 5^{th} and 7^{th} harmonics to the three current waveforms.

Matrix Converter

Alternatively, the Matrix Converter commutation process is different when compared to the VSI.

Figure 4a shows the schematic of the typical bi-directional switch between two different phase line inputs *VA* and *VB* and the output *Va*.



a) b)

Fig. 4: a) Matrix Converter bi-directional switches for inputs *VA*, *VB* and output *Va*, b) Matrix Converter timing diagram showing typical device sequencing when using four-step semi-soft current commutation strategy, from switch A to switch B, when the current direction is positive

The commutation from voltage phase input *VA* to voltage phase input *VB* when the current is positive is being studied. Once the current direction is fixed to be positive (from the mains to the load) the other two possibilities are *VA* greater than *VB* or the opposite, that is to say, *VB* larger than *VA*. The switching timing diagram for the IGBTs *T1*, *T2*, *T3* and *T4* is illustrated in figure 4b. Notice how the output voltage transition depends on which of the both phase voltages inputs is larger defining the time t_{comm}.

Matrix Converters, based on current commutation, have inherently a much better behaviour during commutation, as it can be seen from figure 4b where the well-known four-step semi-soft current commutation process is applied [7] [12]. The current direction is always known and hence the voltage uncertainty (during t_{comm}) is much less (typically 200 ns, being even possible to reduce it to zero). This fact plays an important role for the minimisation of converter non-linear characteristics, and consequently, the HF injection technique will work much better.

IV. Experimental results

The proposed injection method has been tested on an off-the-shelf SMPMSM using both a VSI with dead time compensation, and a Matrix Converter, whose specifications are listed in table I. The estimated rotor position has been used for orientation of the vector control as well as for position and speed feedback in sensorless position control. All the algorithms have been programmed in C code using Texas Instruments DSP.

Table I: Specifications of SMPMSM, VSI and Matrix Converter

SMPMSM		VSI		Matrix Converter	
Rated torque / Rated power	12.2 N·m / 3.83 kW	Position controller	Lag controller	Position controller	P controller
Number of pole pairs	3	Speed controller	P controller	Speed controller	PI controller
Number of stator slots	18	Switching device	IGBT 1200 V, 50 A	Switching device	IGBT 1200 V, 35 A
Nominal speed	3000 rpm	Dead time	2 μs	Dead time	1+0.2+0.5 μs
Maximum cogging	0.23 N·m	Rig inertia	0.0153 kg·m^2	Rig inertia	0.0310 kg·m^2

It should be noted that although the same SMPMSM was used with both inverters, the loading rigs were slightly different. For the VSI fed drive, an AC dynamometer was used, whereas for the Matrix Converter drive, a DC dynamometer was employed. The AC load machine had a lower inertia than the DC load machine, and therefore the acceleration at rated torque and speed settling are slightly slower for the Matrix Converter tests.

Figure 5 shows the speed reversal from 30 rpm to –30 rpm under sensorless speed control with no load. Figure 5a shows the rotor speed, rotor position, estimated rotor position and estimation error under sensorless reversal speed control with no load for the VSI with dead time compensation. Figure 5b shows the estimation achieved when a Matrix Converter is used, although in this case no compensation is used.

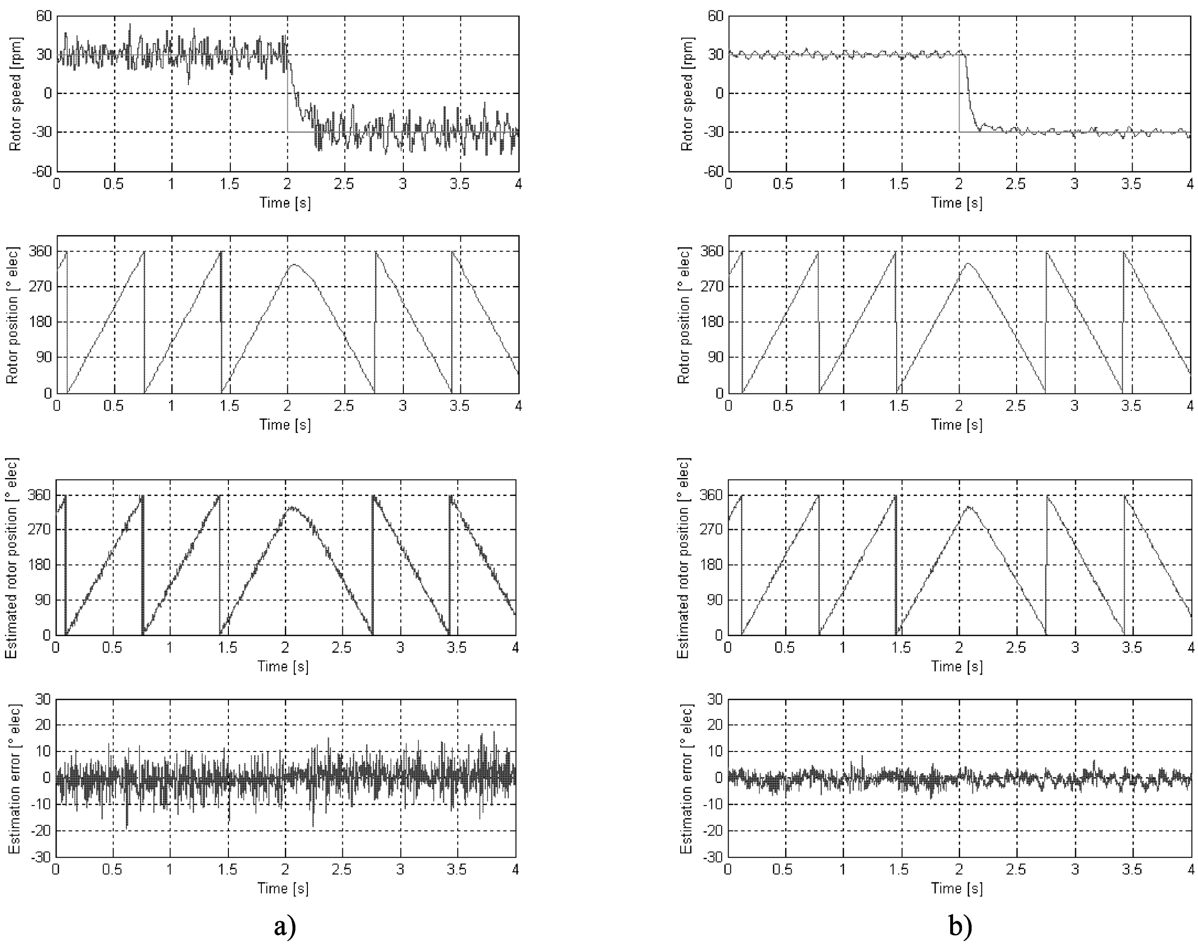


Fig. 5: Rotor speed, rotor position, estimated rotor position and estimation error under sensorless reversal speed control with no load. a) Using VSI, b) Using Matrix Converter

From figure 5 an oscillation can be seen in the speed response. This is due to cogging torque. The motor used has 6 slots per stator phase, which introduces a distortion in the speed estimate at a rate of six times per electrical period. The speed controller naturally tries to compensate for this and therefore introduces a corresponding ripple on the real speed.

From figure 5 it is apparent that the HF injection method for sensorless speed control works much better on the Matrix Converter, even without further compensation.

The position control was tested using a series of positive and negative steps in position demand corresponding to half a mechanical turn, i.e. 540° electrical. The test was performed under no load and half load, and the results are shown in figure 6 and figure 7.

It should be noted that the position controller used for the VSI fed machine was Proportional only, resulting in steady state error most noticeable under load. It proved impossible to design a stable Proportional plus Integral controller due to the increased noise on the speed estimate [13]. The benefit of using the Matrix Converter is obvious – the lower noise allows the design of a PI position control and the elimination of steady state error. Note again the different inertias of the loading systems has a small influence on the rate of change of position.

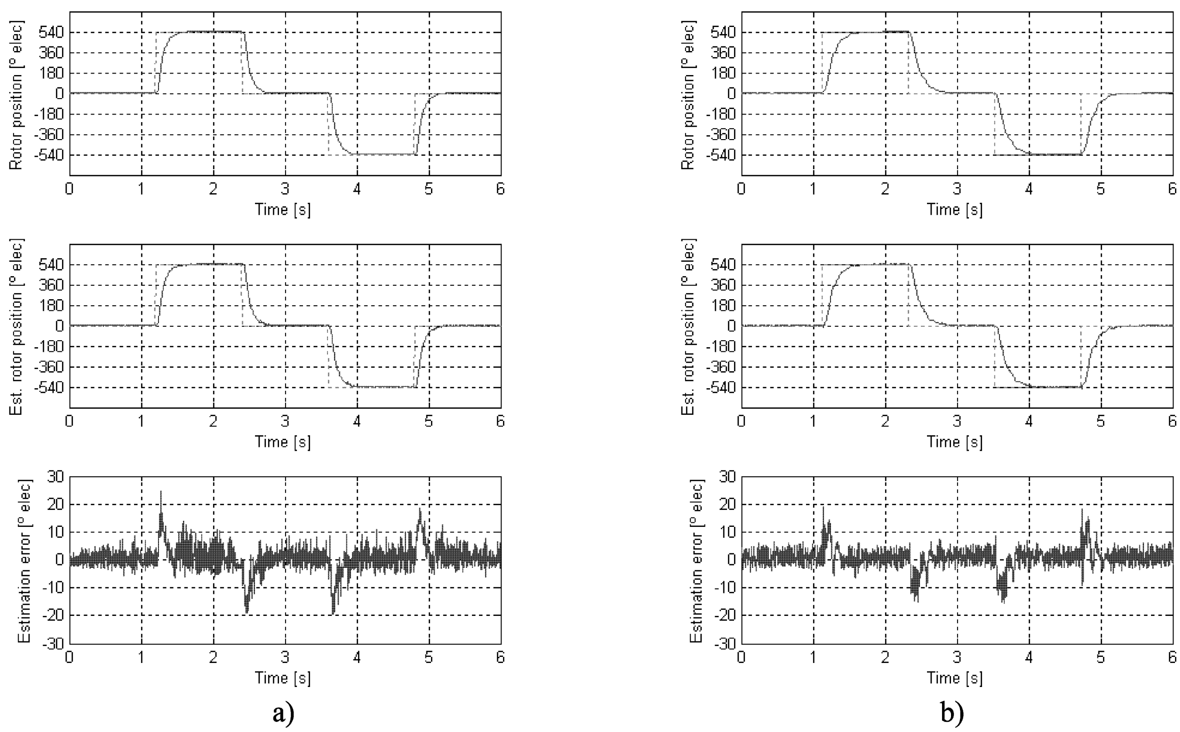
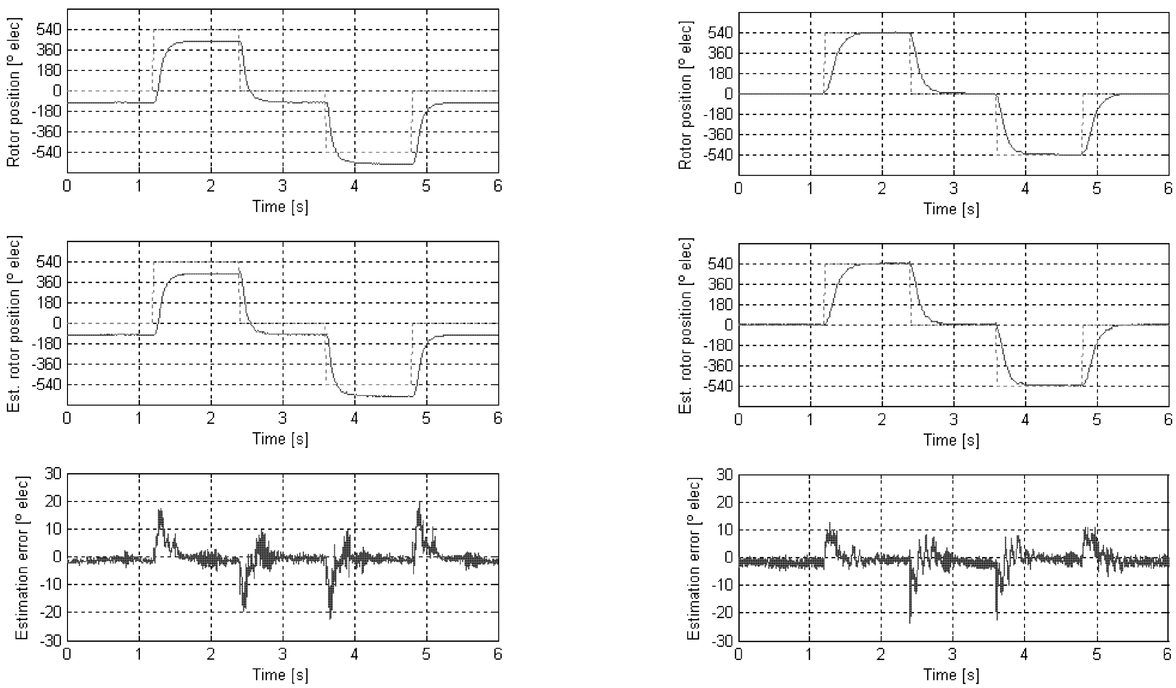


Fig. 6: Rotor position, estimated rotor position and estimation error under sensorless position control with no load. a) Using VSI, b) Using Matrix Converter



a) b)

Fig. 7: Rotor position, estimated rotor position and estimation error under sensorless position control with half load. a) Using VSI, b) Using Matrix Converter

From figures 6 and 7 small oscillations in the position response can be seen, and these are again due to cogging torque. Both VSI and Matrix Converter plots show good position tracking with a high loop bandwidth, but the control using VSI is faster, because its experimental rig has got half the inertia of the Matrix Converter rig.

The error using the Matrix Converter with no load is no bigger than 15° electrical (5° mechanical) during position transients and about 5° electrical (1,66° mechanical) at steady state. With half load the steady state error is smaller, about 2° electrical (0,66° mechanical).

The Spatial Modulation Profiling (SMP) [10] has been used in both systems to achieve the best possible sensorless position control. The SMP technique uses tables to record the harmonics of the position signals as a function of rotor position angle. During operation, the pre-commissioned tables are used to compensate for the distortions in the position signals in the time domain. Using the VSI it is impossible to achieve good control without the SMP compensation. However it is possible to achieve sensorless position control with the Matrix Converter, without using the SMP. Figure 8 shows the performance of this system, on no load and half load.

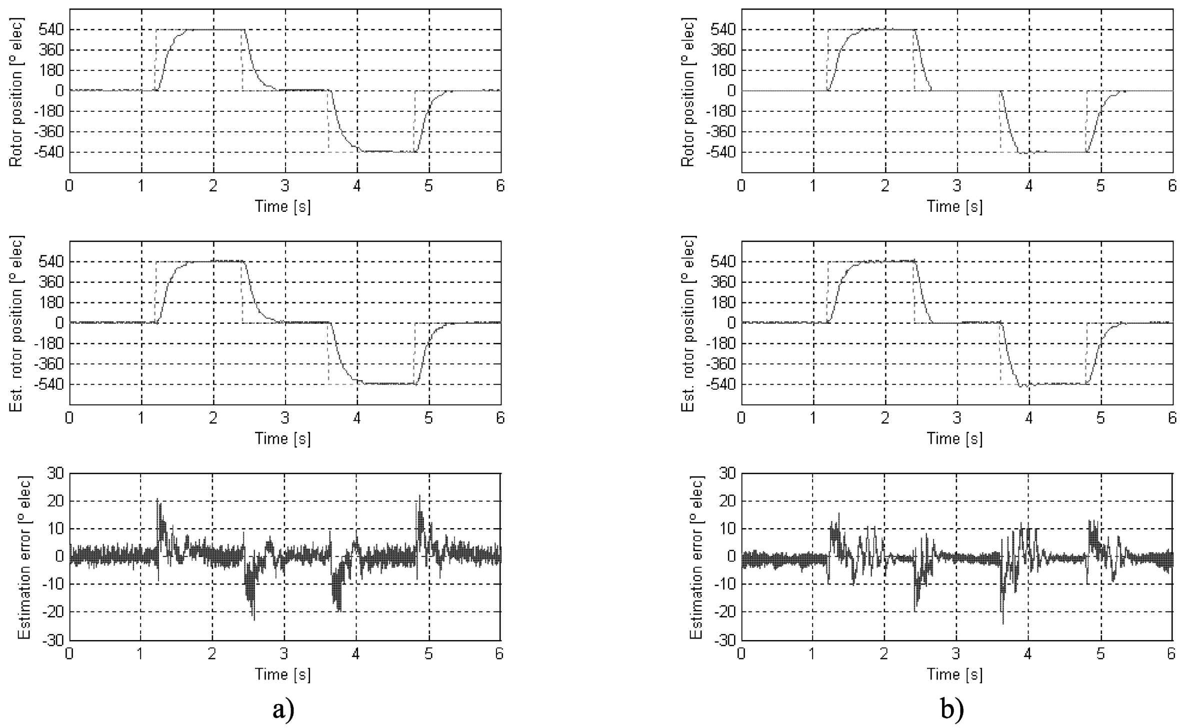


Fig. 8: Rotor position, estimated rotor position and estimation error under sensorless position control without SMP using Matrix Converter. a) No load, b) Half load

Also the response of the sensorless position control loop to step changes in load has been tested. A zero position reference is used. The load step is achieved by a change in the torque reference of the load machine from 0 to half nominal torque. The position and speed responses are shown in figure 9. Both systems respond to this disturbance with a maximum transient speed of –55 rpm approximately, but the Matrix Converter control algorithm reduces the position error to zero.

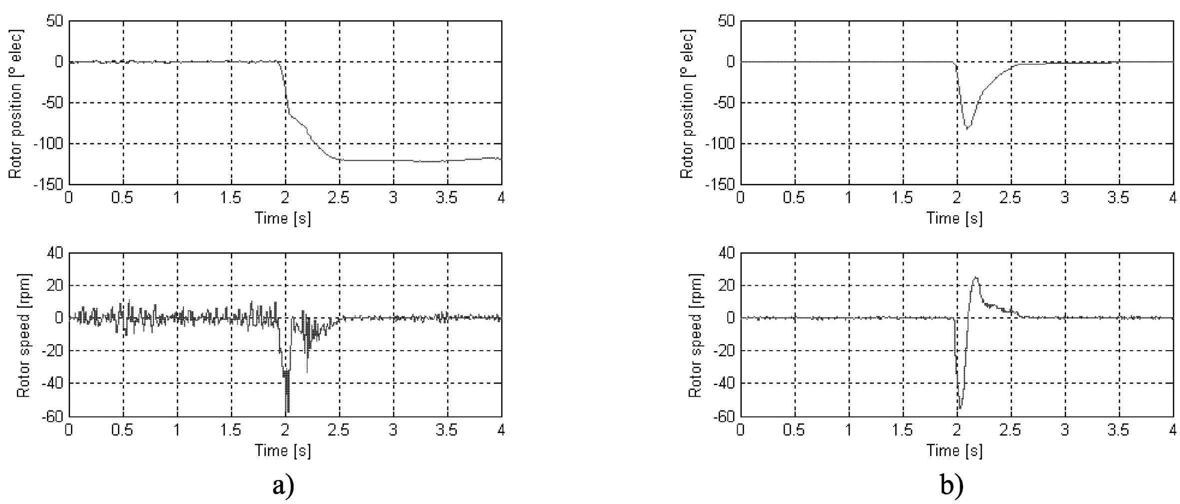


Fig. 9: Rotor position and rotor speed under sensorless zero position control.
a) Using VSI, b) Using Matrix Converter

These experimental results clearly demonstrate that the performance of the Matrix Converter sensorless position drive without any compensation of device non-linearities is better to that of the VSI inverter with dead time compensation.

V. Conclusion

The use of the Matrix Converter, instead of the conventional VSI, for HF injection sensorless position control for SMPMSM, has been presented. The minimization of the non-linear characteristics, such as voltage drop and more importantly dead time and current clamping, means that the Matrix Converter behaves like an ideal power converter and consequently improves the quality of the High Frequency injection signals and the resultant position estimate. This improvement is so significant that it is now possible to remove the SMP compensation, extra compensation that the VSI drive always requires. The remaining problem is now to accurately track the influence of the stator slots, so that the cogging effect can be removed from the speed estimate, and a feedforward term for the cogging effect can be employed to improve the response of the position control loop. Work here is on-going.

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