

Sensorless Control of Surface Mounted Permanent Magnet Synchronous Motors Using Matrix Converters

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Summary: This paper investigates the influence of the power converter on the performance of Surface Mounted Permanent Magnet Synchronous Motor drives, which employ High Frequency voltage injection to achieve low and zero speed control. Experimental results demonstrate the remarkable performance of the sensorless speed and position control employing the Matrix Converter and the contributions of the Space Modulation Profiling technique. 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.

Keywords:

sensorless control,
permanent magnet
synchronous motor,
matrix converters

1. INTRODUCTION

The availability of higher-strength magnet materials, improved power switches, and new integrated circuits are providing the ingredients for new Permanent Magnet Synchronous Machines (PMSM) and drive configurations, with important commercial implications. The PMSM have the potential to replace the induction motor in a number of industrial, commercial and domestic variable speed applications.

The control of synchronous AC machines requires the knowledge of the rotor position and speed for field orientation and closed loop speed and position control. Rotor shaft sensors are usually fitted, increasing the total cost of the drive and reducing its reliability. Nevertheless, sensorless control at zero speed is still a challenge, especially for Surface Mounted Permanent Magnet Synchronous Machines (SMPMSM), where the magnet saliency is rather small. For this reason extensive research has been carried out to develop sensorless strategies. Methods, based on the model of the machine in which the back-EMF is integrated to determine the linkage flux, have been successfully implemented [1–3]. However, all these techniques fail at low speed due to lack of a reliable back-EMF estimate deriving from integrator drift and increasing sensitivity to errors in the parameter estimation. A second type of sensorless strategy suitable for zero and low speed operation is the so called “injection method” [4–7]. In this method High Frequency (HF) signals are injected into the machine. The position dependent inductance causes modulation in the resulting HF current that give the position information. This technique has been reported for high saliency machines such SR motors and buried magnet PM machines [8–10]. In surface mounted PM machines, characterised by small saliency, the technique has been tried [11] using the saliency created by main flux saturation, but operation was only possible at low loads.

Further problems for position estimation arise from the

use of standard inverters for power conversion. The converter non-linearities such as deadtime, device voltage drop and current clamping at zero current values [12–15] cause distortion in the estimated position. In recent years there has been much development of the direct AC-AC converter named Matrix Converter (MC), and it is claimed that this can produce an output waveform free of the influence of voltage drops and deadtime delays, i.e. behaves as an ideal linear voltage converter [16, 17].

The work presented in this paper compares the use of a Matrix Converter and a conventional Voltage Source Inverter (VSI) in a sensorless SMPMSM drive, which uses HF voltage injection to obtain the estimated position. Experimental results demonstrate the excellent performance of the Matrix Converter sensorless control system.

2. HIGH FREQUENCY INJECTION FOR SENSORLESS 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.

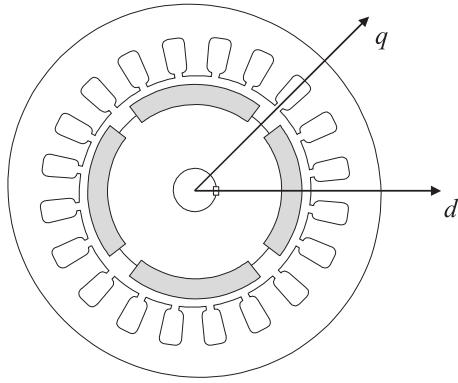


Fig. 1. Surface mounted PM machine with semi-inserted magnets

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

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

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

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

$$\bar{L}_s = \frac{L_q + L_d}{2} \quad (3)$$

and the saliency is given by equation (4):

$$\Delta L_s = \frac{L_q - L_d}{2} \quad (4)$$

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 [12].

$$\mathbf{v}_i = \begin{bmatrix} v_{ci} \\ v_{\beta i} \end{bmatrix} = \hat{V}_i \begin{bmatrix} -\sin(\omega_i t) \\ \cos(\omega_i t) \end{bmatrix} \quad (5)$$

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

$$\mathbf{i}_i = \begin{bmatrix} i_{ci} \\ i_{\beta i} \end{bmatrix} \approx \begin{bmatrix} I_0 \cos(\omega_i t) + I_1 \cos(2\theta_r - \omega_i t) \\ I_0 \sin(\omega_i t) + I_1 \sin(2\theta_r - \omega_i t) \end{bmatrix} \quad (6)$$

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

$$I_0 = \frac{\hat{V}_i \bar{L}_s}{L_d L_q \omega_i} \quad (7)$$

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

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

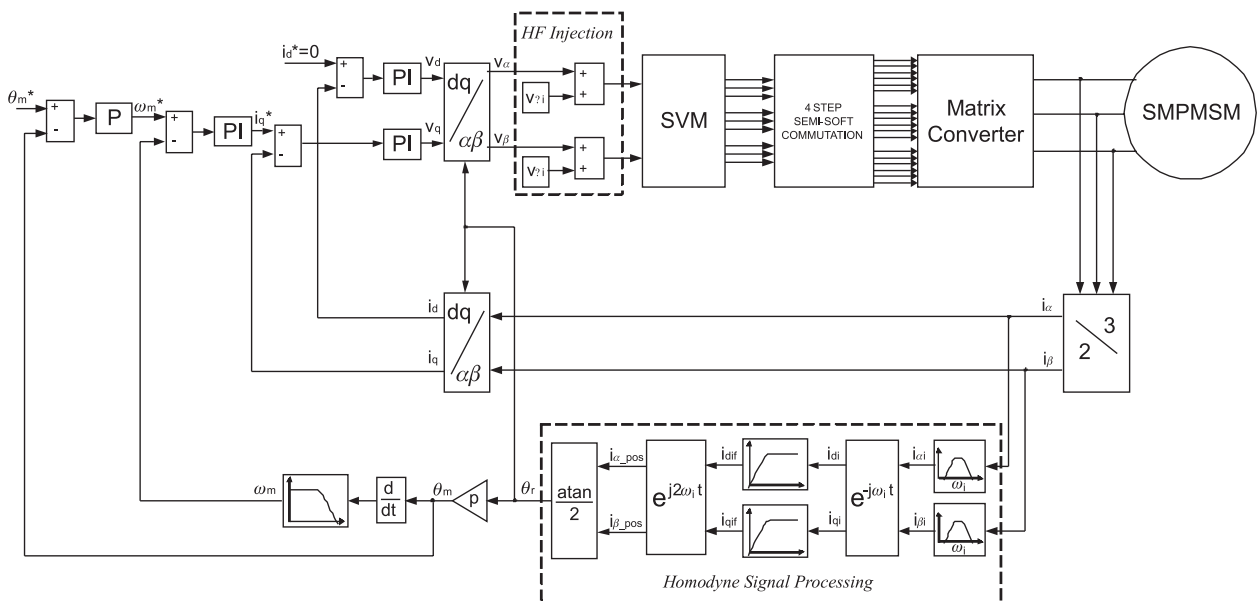


Fig. 2. Diagram for the sensorless position control of a SMPMSM using Matrix Converter

signal from the total high frequency current the Homodyne Signal Processing [4, 12], shown in Figure 2, must be implemented.

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 θ_r can be then extracted directly by an arc tangent.

$$\begin{bmatrix} i_{\alpha_pos} \\ i_{\beta_pos} \end{bmatrix} \approx \begin{bmatrix} I_1 \cos(2\theta_r) \\ I_1 \sin(2\theta_r) \end{bmatrix} \quad (9)$$

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 [11]. This will produce harmonics in the position signals in equation (9) and in turn will produce angle estimation errors.

3. 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 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 [14, 15].

3.1. 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. 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 5th and 7th harmonics to the three current waveforms.

3.2. Matrix Converter

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

Figure 3 shows the MC general scheme and its bi-directional switches between two different phase line inputs V_A and V_B and the output V_a .

The commutation from voltage phase input V_A to voltage phase input V_B 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 V_A greater than V_B or the opposite, that is to say, V_B larger than V_A . The switching timing diagram for the IGBTs $T1$, $T2$, $T3$ and $T4$ is illustrated in Figure 4. 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 4 where the well-known four-step semi-soft current commutation process is applied [16, 17]. 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

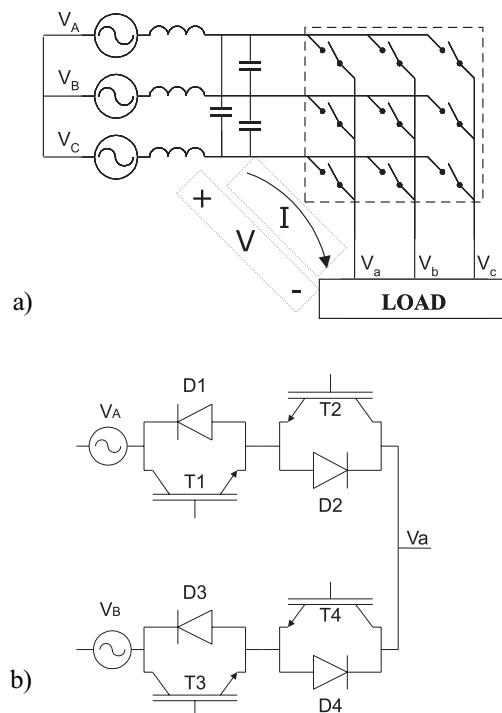


Fig. 3. a) Matrix Converter scheme with voltage and current polarities. b) Matrix Converter bi-directional switches for inputs V_A , V_B and output V_a

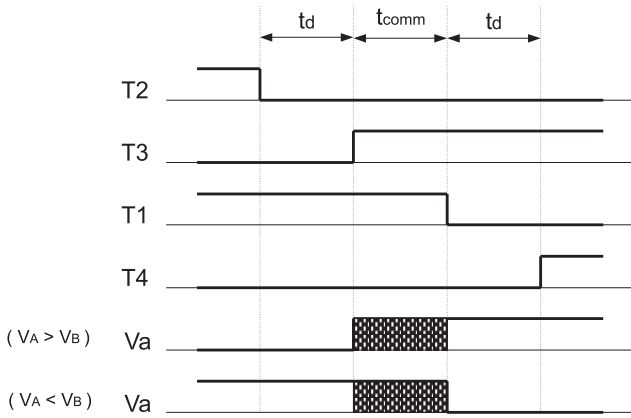


Fig. 4. Timing diagram showing typical device sequencing when using four-step semi-soft current commutation strategy, from switch A to switch B, when the current direction is positive

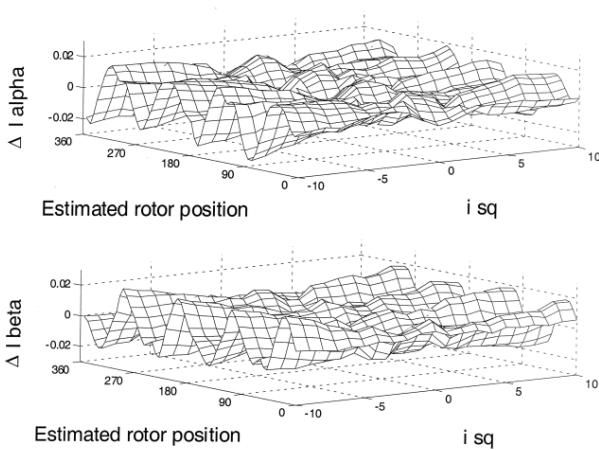


Fig. 5. SMP tables

important role for the minimisation of converter non-linear characteristics, and consequently, the HF injection technique will work much better.

4. SPACE MODULATION PROFILING

To achieve good sensorless control the accuracy of the rotor position estimation needs to be improved further. In this work this is done by means of Space Modulation Profiling (SMP).

The periodicity of the error with rotor position can be exploited to improve the rotor position estimation. The correction of the position signals has been carried out for individual harmonics, this method has the advantage of only requiring the amplitude and phase (only two values) per each harmonic to be cancelled. This approach is suitable when only a small number of harmonics are to be suppressed. To compensate for position signals with errors of a richer spectrum, such as those produced by any remaining inverter non-linearities and any geometrical asymmetry in the SMPMSM, the SMP technique proposed in [18] is better suited.

4.1. Commissioning of the SMP tables

In the commissioning process, the profile of expected differences between saliency position signals and their ideal values are calculated and stored in the SMP tables. The signal processing for extraction of the profiles is performed off-line. In this research the commissioning process is undertaken with the SMPMSM drive operated in sensed torque control. The speed is controlled at an arbitrary value of 60 rpm by the load drive, resulting in 3 Hz excitation frequency and 6 Hz fundamental saliency position signals. The data is captured at a fix rate of 10/3 kHz during 6 seconds (20000 samples). Similar data captures are repeated for different torque current references for the whole load range, from -10 A to 10 A in intervals of 0.5 A. The profile is created for each individual torque level. The fundamental component of the saliency position signal is extracted by narrow Butterworth Band Pass filter centred at 6 Hz and the spectral contents of the position signals limited to 600 Hz by a Low Pass filter. The data is applied backwards and forwards to the filters using the “filtfilt” Matlab command to achieve a non-causal filters that preserve the signals phase. The difference between both signals is calculated and stored as a function of the rotor position. This is done by dividing the complete rotor revolution into a discrete number of intervals (60 was used in this work), all the error measurements corresponding to the same angle interval are averaged to produce the typical error for that position. Approximately 50 samples per position interval, corresponding to 10 different revolutions have been used in the calculation of each average.

The profiling procedure is repeated for the data obtained with the different torque references generating the two-dimensional SMP tables shown as surfaces in Figure 5.

4.2. Load phase shift compensation

The use of the SMP tables allows the extraction of the fundamental component of the position signal, enabling the estimation of the saliency position $\hat{\theta}_\delta$. Under no load this position coincides with the rotor flux direction, or d axis. Under load, the stator saturation is influenced by the stator currents and will produce a shift of the saliency relative to the rotor flux axis, producing an offset between the estimated angle and the actual rotor position. In machines with a saliency dominated by rotor geometry this shift is negligible. Nevertheless, when saturation induced saliency is being tracked as in SMPMSM, the shift of the saliency becomes significant and has to be taken into account to achieve good orientation. This phase shift is also quantified during the commissioning process by averaging the phase difference between the saliency angle $\hat{\theta}_\delta$ and the measured rotor position $\hat{\theta}_r$ for each load value.

Because the saliency is influenced by the stator flux, the dynamic of the phase shift can be approximated by the dynamic of the stator current. Therefore, the phase compensation can be performed using the measured value of i_{sq} or, if the reference value i_{sq}^* is used instead, a filter is applied to emulate the dynamics of the q-axis current loop. This second alternative is preferred because it results in a smoother signal free from the components at injection frequency; the same torque current estimation is used to address the SMP tables.

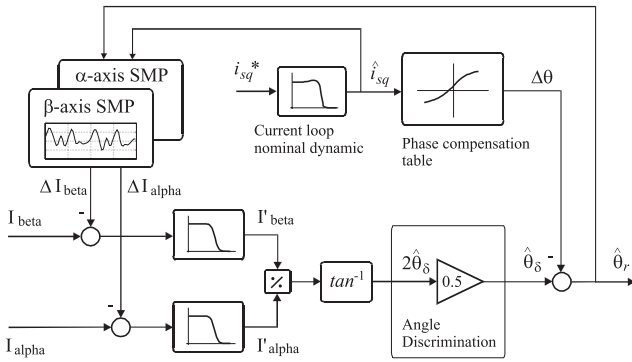


Fig. 6. SMP and phase-shift correction for rotor position estimation

Finally the complete rotor position estimation including the SMP and the phase compensation table is shown in Figure 6.

5. 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 1. The estimated rotor position has been used for orientation of the vector control as well as for position and speed feedback in sensorless control. All the algorithms have been programmed in C code using Texas Instruments DSP.

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 7 shows the speed reversal from 30 rpm to -30 rpm under sensorless speed control with no load. Figure 7a 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 7b shows the estimation achieved when a Matrix Converter is used, although in this case no dead time compensation is used.

From Figure 7 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 7 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 the results are shown in Figure 8.

It should be noted that the speed 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. 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.

From Figure 8 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.

A deeper analysis is done in the Matrix Converter system, where the contribution of the SMP is clearly shown. Figure 9 shows the position signals before and after the SMP. In order to do the comparison in the frequency domain, the FFT of both signals is calculated. Hence, Figure 10 shows the FFT before and after the SMP, respectively.

Figure 11a shows the speed reversal from 30 rpm to -30 rpm under sensorless speed control without SMP, whereas figure 11b shows the same test but with SMP.

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.

Table 1. Specifications of SMPMSM, VSI and Matrix Converter

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

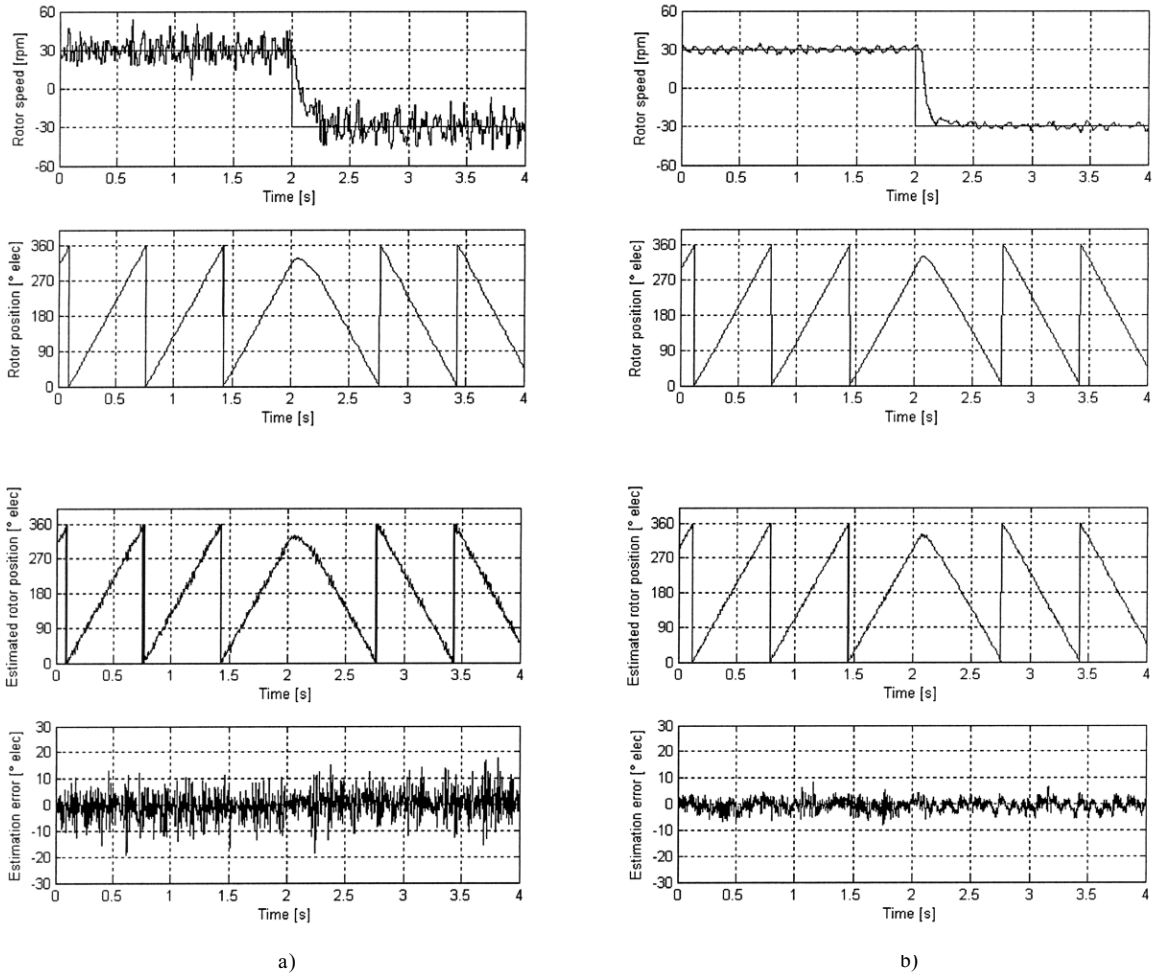


Fig. 7. Rotor speed, rotor position, estimated rotor position and estimation error under sensorless reversal speed control with no load. a) Using VSI, b) Using Matrix Converter

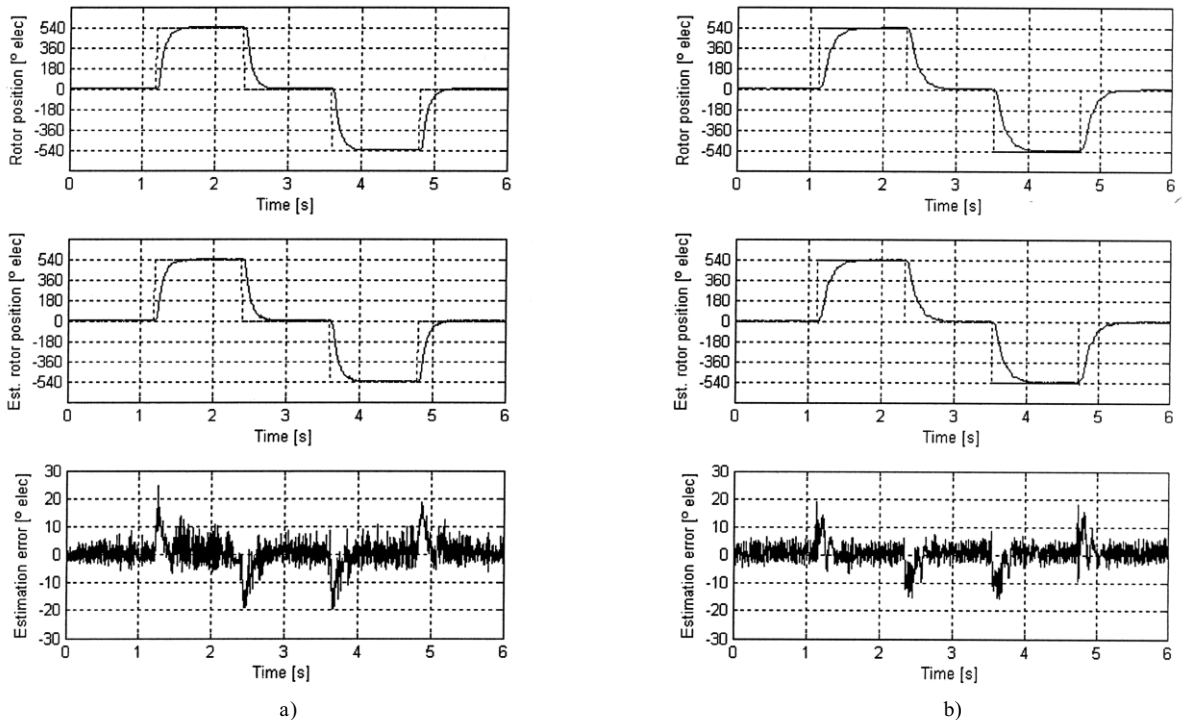


Fig. 8. Rotor position, estimated rotor position and estimation error under sensorless position control with no load. a) Using VSI, b) Using Matrix Converter

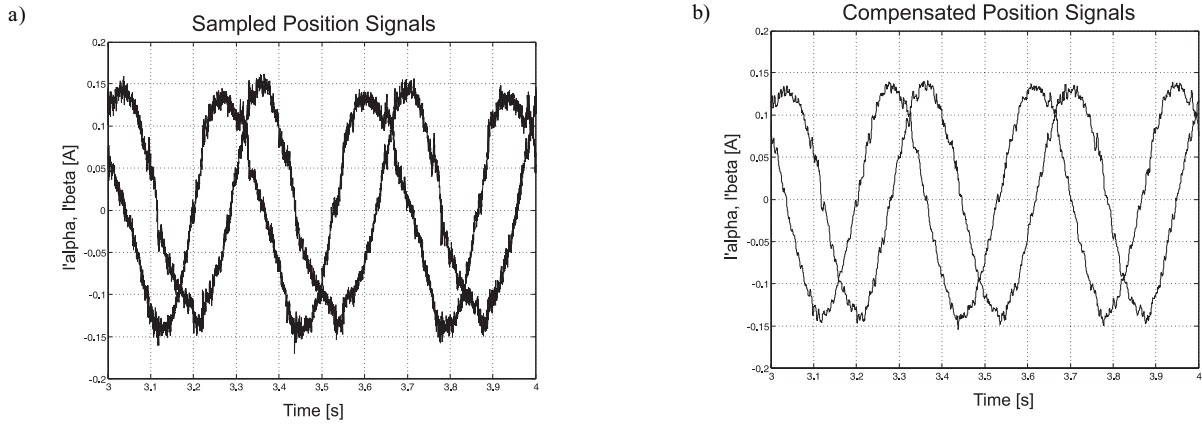


Fig. 9. Position signals under full load. a) Before SMP, b) After SMP

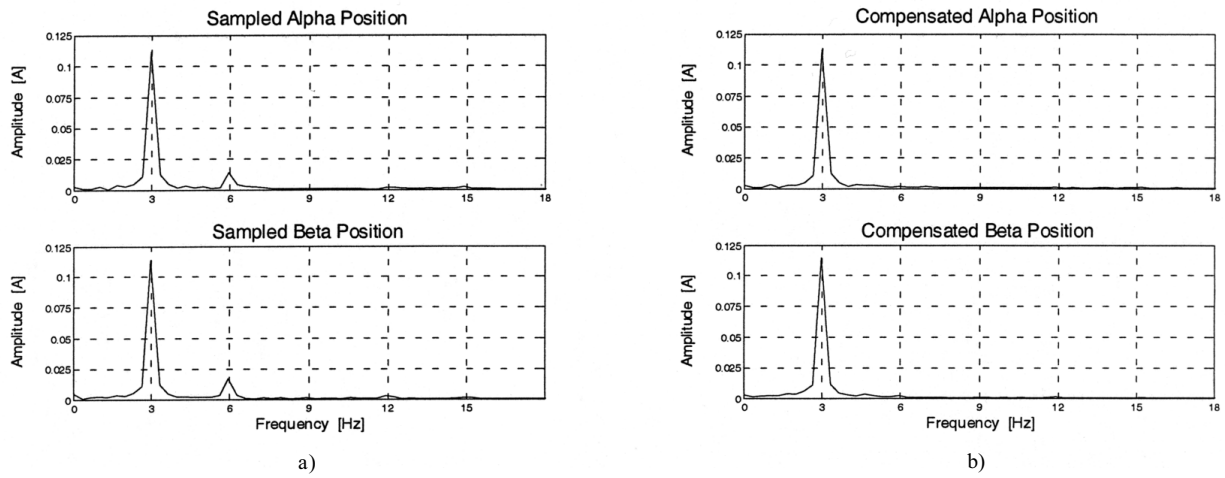


Fig. 10. FFT of the position signals under full load. a) Before SMP, b) After SMP

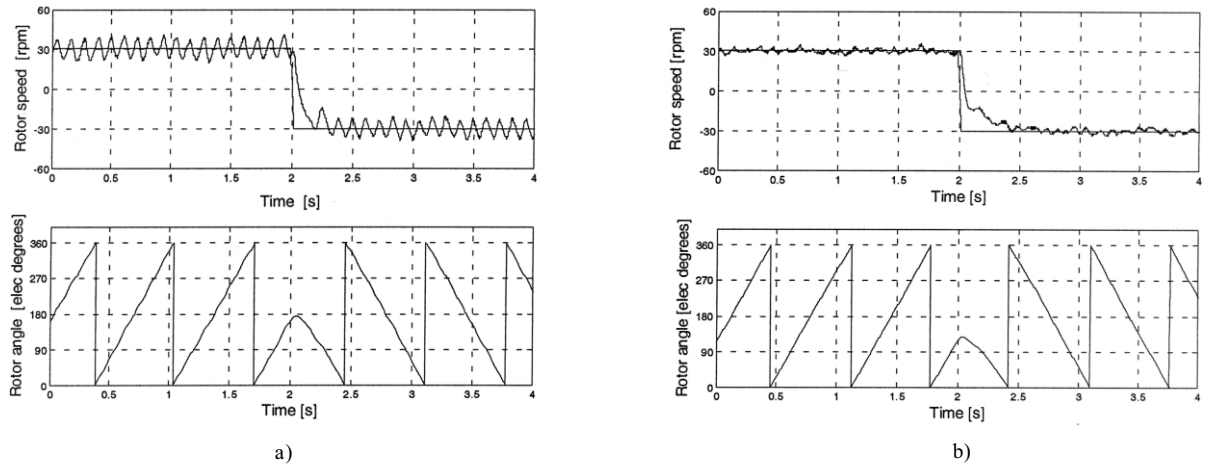


Fig. 11. Rotor speed and angle under sensorless speed control. a) Without SMP, b) With SMP

6. CONCLUSIONS

The use of the Matrix Converter, instead of the conventional Voltage Source Inverter, for High Frequency Injection Sensorless for Surface Mounted PMSM drives, has been presented. The main advantages are outlined. The minimisation of the non-linear characteristics, such as voltage drop and more importantly dead time and current clamping, allows the Matrix Converter to achieve a much more linear

characteristic and consequently to improve the overall sensorless performance.

Experimental results demonstrate the superior behaviour of the position estimation when using a Matrix Converter. The Space Modulation Profiling technique is used to further improve the angle estimation.

Finally, sensorless speed and position control is achieved and its experimental results shown.

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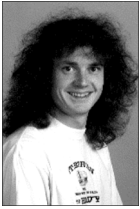
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