SENSORED and SENSORLESS CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS USING MATRIX CONVERTERS

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Abstract: 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 speed control. The effects of IGBT voltage drop, deadtime and deadtime compensation on position estimation are discussed and the use of Matrix Converter is proposed to reduce these effects. Space Modulation Profiling technique is used to further improve the estimated angle. Experimental results demonstrate the remarkable performance of the sensorless speed control employing the Matrix Converter and the contributions of the Space Modulation Profiling technique.

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 adding to the total cost of the drive and reducing its reliability. Nevertheless, sensorless at zero speed is still a challenge, especially for the 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 HF voltage (or current) signals are injected into the machine terminals. The position dependent inductance causes modulation in the resulting HF current (voltage) 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 position estimates. In recent years there has been much development of the direct AC-AC converter-Matrix Converter [16]-[17], 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 in a low speed sensorless SMPMSM drive, which uses HF voltage injection to obtain the position estimate. Experimental results demonstrate the excellent performance of the Matrix Converter speed sensorless control system.

2. HIGH FREQUENCY INJECTION FOR SENSORLESS CONTROL

An AC synchronous 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 $L_q$. This difference is caused by asymmetry in the rotor design, as in the case of synchronous reluctance and interior magnet PM machines and/or by main flux saturation, as in surface mounted PM machines. The $\alpha$-$\beta$ model of a synchronous PM machine in the stator reference frame including the saliency is given by equation (1). 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.

\[
\begin{bmatrix}
    v_a \\
    v_\beta \\
    \psi_a \\
    \psi_\beta \\
\end{bmatrix} =
\begin{bmatrix}
    R_1 & 0 & sI_a & 0 & \hat{\psi}_a \\
    0 & R_1 & 0 & sI_\beta & \hat{\psi}_\beta \\
    \hat{\psi}_a \\
    \hat{\psi}_\beta \\
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_\beta \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
    \psi_a \\
    \psi_\beta \\
\end{bmatrix} =
\begin{bmatrix}
    L_d - \Delta L_d \cos(2\theta) & -\Delta L_d \sin(2\theta) \\
    -\Delta L_d \sin(2\theta) & L_q + \Delta L_q \cos(2\theta) \\
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_\beta \\
\end{bmatrix} +
\begin{bmatrix}
    \tilde{v}_a \\
    \tilde{v}_\beta \\
\end{bmatrix}
\cos(\theta) \\
\sin(\theta)
\]

(1)

where the inductances are as follows:

\[
L_\alpha = \frac{L_a + L_d}{2} \quad \Delta L_\alpha = \frac{L_a - L_d}{2}
\]

(2)

To extract the position information contained in the inductance matrix of equation (1), the HF rotating voltage vector given by equation (3) is added to the stator voltages [12] as shown in Fig 1.

\[
\begin{bmatrix}
    v_a \\
    v_\beta \\
\end{bmatrix} = \begin{bmatrix}
    I_d \sin(\omega_t t) \\
    \cos(\omega_t t)
\end{bmatrix}
\]

(3)

If the injection frequency $\omega_t \gg \omega_0$; where $\omega_0$ is the synchronous excitation frequency, the induced HF currents in the stator windings are given by equation (4).

\[
i_d = \begin{bmatrix}
    i_a \\
    i_\beta \\
\end{bmatrix} = \begin{bmatrix}
    I_d \cos(\omega_0 t) + I_1 \cos(2\theta - \omega_0 t) \\
    I_1 \sin(\omega_0 t) + I_1 \sin(2\theta - \omega_0 t)
\end{bmatrix}
\]

(4)

where

\[
I_d = \frac{\tilde{V} L_a}{L_a L_q \omega_0}; \quad I_1 = \frac{\tilde{V} \Delta L_q}{L_d L_q \omega_0}
\]

(5)

In equation (4) 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 synchronous filter of Fig 2 is implemented. The Band Pass Filter removes the fundamental component from 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 (6). The angle $2\theta_t$ can be then extracted directly by an arc tangent ($\mathrm{atan}$).

\[
\begin{bmatrix}
    i_{a, \mathrm{pos}} \\
    i_{\beta, \mathrm{pos}} \\
\end{bmatrix} \approx \begin{bmatrix}
    I_1 \cos(2\theta_t) \\
    I_1 \sin(2\theta_t)
\end{bmatrix}
\]

(6)

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-linearity i.e. dead time becomes significant. Second, the saliency is not sinusoidally distributed and furthermore it’s 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 (6) and in turn will produce angle estimation errors.

\[
i_a = \begin{bmatrix}
    I_0 \\
    \tan^{-1}(\omega t)
\end{bmatrix}
\]

Fig 1. Sensorless speed control structure with the HF voltage injection.

Fig 2. Synchronous filter for demodulation of HF currents.

3. CONVERTER NON-LINEAR CHARACTERISTICS

Among the converter non-linear characteristics, 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.

Fig. 3 shows the typical waveform patterns for the conventional VSI during commutation of one-leg. Note the effect of the dead time introduces an uncertainty for the voltage output (shown in dotted area in Fig. 3) during the whole dead time (td). The current direction is needed to know exactly which anti-parallel diode will conduct during the dead time and consequently to know
the output voltage. Moreover, any dead time compensation techniques, such as the one based on the edge shifting, should be applied to compensate such uncertainty \[14\] \[15\].

\[ V_{dc} \]
\[ T_1 \]
\[ D_1 \]
\[ Va \]
\[ T_2 \]
\[ D_2 \]
\[ Va \]

**Fig. 3** Voltage Source Inverter timing diagram showing typical device sequencing with commutation from upper to lower switches.

### 3.2. Matrix Converter.

Alternatively, the MC commutation process is different when compared to the VSI. Fig. 4 shows the MC general scheme and one of its bi-directional switch between two different phase line inputs \( V_A \) and \( V_B \) and the output \( V_a \).

\[ V_A \]
\[ V_B \]
\[ V_C \]
\[ + \]
\[ I \]
\[ V_a \]
\[ V_b \]
\[ V_c \]
\[ LOAD \]

**Fig. 4.** Top: Matrix Converter scheme with voltage and current polarities. Down: Matrix Converter topology between two inputs and one output.

The commutation from voltage phase input \( V_A \) to voltage phase input \( V_B \) when the current is positive is being studied. The switching timing diagram when the well established four commutations step is applied is illustrated in Fig. 5 \[16\][17].

\[ T_2 \]
\[ T_3 \]
\[ T_1 \]
\[ T_4 \]
\[ (V_A < V_B) \]
\[ V_a \]
\[ (V_A > V_B) \]

**Fig. 5.** Four step switching commutation strategy from switch A to switch B and for positive current. Notice how the output voltage \( V_a \) changes depending on the input voltages.

Typical time for the effective dead time (\( t_d \)) where there is voltage uncertainty is just of 200ns, which is much lower than the equivalent time for the VSI. Moreover, the edge shifting technique is inherent to the current based commutated MC, since the current directions are always known. Hence, the timing obtained for the same commutation as Fig. 5 but for negative currents is as Fig. 6 illustrates.

\[ T_2 \]
\[ T_3 \]
\[ T_1 \]
\[ T_4 \]
\[ (V_A < V_B) \]
\[ V_a \]
\[ (V_A > V_B) \]

**Fig. 6.** Four step switching commutation strategy from switch A to switch B and for negative current. Notice how the edge of all signals have been shifted compared to Fig. 5.

### 4. SPACE MODULATION PROFILING

To achieve good sensorless rotor position 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. In the present work, the correction of the saliency position signals \( I_{alpha} \) and \( I_{beta} \) rather than the direct correction of the angle estimation is favoured. The correction of the position signals has been carried out for individual harmonics, the method having the advantage of only requiring the amplitude and phase (only two values) per 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

In the commissioning process, the profile of expected differences between saliency position signals $I_{alpha}$, $I_{beta}$ 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 sensored 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 \textit{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. This signal processing is represented in the flow diagram of Fig. 7.

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 $\hat{\delta}_s$. 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 $\hat{\delta}_s$ and the measured rotor position $\theta_r$ 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 commanded value 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.

Finally the complete rotor position estimation including the SMP and the saturation shift table is shown in Fig. 9. Here the demanded torque current $i_{sq}^*$ and the estimated rotor position angle $\hat{\delta}_r$ are used to address the SMP tables to obtain the correcting quantities $\Delta I_{alpha}$ and $\Delta I_{beta}$, which are subtracted from the demodulated raw position signals $I_{alpha}$ and $I_{beta}$ and the result filtered to obtain the corrected saliency position signals $I'_{alpha}$ and $I'_{beta}$.
and $I_{\beta}\hat{\delta}$. The saliency angle $2\theta_{\delta}$ is obtained by direct \( \tan^{-1} \) extraction from quotient of these signals. Finally as indicated in this Fig. 9, the saliency angle $\hat{\delta}_{\delta}$ is corrected for the saturation shift depending on the reference torque current $i_{\delta}^\star$ to obtain the rotor position estimation $\hat{\theta}_{r}$. 

5. EXPERIMENTAL RESULTS

Experimental results have been carried out closing the speed and current loops of the SMP-MSM, as Fig. 1 shows. A hf voltage of 30 volts and 1KHz has been injected in order to estimate the rotor position angle.

Table I. Specifications of SMP-MSM, VSI and Matrix Converter

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PMSM</strong></td>
<td><strong>VSI</strong></td>
</tr>
<tr>
<td>Rated power / Number of poles</td>
<td>3.8kW / 6</td>
</tr>
<tr>
<td>Nominal speed / Rated torque</td>
<td>314.15rad/s / 12.2Nm</td>
</tr>
<tr>
<td>Rs / Ld / Lq / Saliency</td>
<td>0.5Ω / 4.35mH / 5.9mH / 0.73</td>
</tr>
<tr>
<td><strong>Matrix Converter</strong></td>
<td></td>
</tr>
<tr>
<td>Switching device</td>
<td>1200V, 35 A, IGBT</td>
</tr>
<tr>
<td>Turn on / turn off / dead time</td>
<td>400ns / 800ns / 2 μs</td>
</tr>
<tr>
<td>diode / IGBT / voltages drops</td>
<td>2V / 3V</td>
</tr>
</tbody>
</table>

Under full load, the contribution of the SMP is much clearer and consequently the worst performance is given by MC without SMP. Again, the MC with SMP achieves the best performance constraining the Angle error within less than 5 electrical degrees. Therefore, the best speed response is obtained as well with the MC with SMP.

A deeper analysis is done in the MC with SMP system, where the contribution of the SMP is clearly shown. Fig. 10 shows the position signals before the SMP and Fig. 11 after the SMP. In order to do the comparison in the frequency domain, a zoom of both signals is carried out an its FFT calculated. Hence, Fig. 12 and 13 show the zoom and the FFT before and after the SMP, respectively.
Fig. 13. FFT of the position signals after SMP compensation.

Fig. 14 shows the speed reversal from 30rpm to –30rpm under sensorless speed control without SMP, whereas Fig15. shows the same test but with SMP. Note how the control of the SMPMSM is good enough not only in steady state but also during the transient. The angle estimation, therefore, is good enough to achieve such a sensorless speed control. From Fig 14 it might be seen, however, a small oscillation in the speed response. This is due to motor cogging (which acts as a perturbation on the speed loop and hence the \( I_q \) demand). In Fig. 15 it might be observed how the inclusion of the SMP reduces such oscillation.

6. CONCLUSIONS

The use of the Matrix Converter, instead of the conventional Voltage Source Inverter, for High Frequency Injection Sensorless for Surface Mount 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 behavior 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 control is achieved and its experimental results shown.

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8. REFERENCES
