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A Robust Hybrid Current Control for Permanent Magnet Synchronous Motor Drive

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Abstract—Recently, the Permanent Magnet Synchronous Motor (PMSM) find a widespread utilization in modern adjustable AC drives. This is achieved by using current controlled Voltage Source Inverter (VSI) systems. Because of its ease implementation, fast current control response and inherent peak current limiting capability, hysteresis current control is considered as the simplest technique used to control the motor currents for AC machines. On the other hand, the ramp comparator controller has some advantages, such as limiting maximum inverter switching frequency to the carrier triangular waveform frequency and producing well-defined harmonics. In order to take advantage of the position features of both these two controllers, this paper presents the design and software implementation of a hybrid current controller. The proposed intelligent controller is a simultaneous combination and contribution of the hysteresis current controller and the ramp comparator. Comparisons using simulations on a 0.9-kW PMSM confirm that the proposed hybrid current controller gives better performance and has the advantage of conceptual simplicity. In particular, harmonic spectra of the stator current, obtained by using a fast Fourier transform, are used for comparison purposes.

Index Terms—PMSM, robustness, hysteresis controller, ramp comparator, hybrid controller.

NOMENCLATURE

\begin{align*}
  s, (r) & = \text{stator (rotor) index;} \\
  d, q & = \text{synchronous reference frame index;} \\
  V & = \text{voltage;} \\
  I & = \text{current;} \\
  \phi_p & = \text{permanent magnet flux;} \\
  T_e & = \text{electromagnetic torque;} \\
  T_l & = \text{load torque;} \\
  R & = \text{resistance;} \\
  L & = \text{inductance;} \\
  \omega_p & = \text{angular speed;} \\
  \theta & = \text{rotor position;} \\
  f & = \text{viscosity coefficient;} \\
  J & = \text{rotor inertia;} \\
  n_p & = \text{pole pair number;} \\
  K_T & = K_T = 3 n_p \phi_p / 2; \\
  p & = \text{derivative operator.}
\end{align*}

I. INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) drives are today gradually replacing classic dc drives in a large number of industrial applications, taking full advantage of key features of PM motors, such as compactness, efficiency, robustness, reliability, and shape adaptation to the working environment [1-2].

Substantial development efforts have been devoted to the application of various classes of robust control techniques in order to exploit the efficiency and extremely fast dynamic capabilities of the PMSM. More specifically, there have been several papers describing applications of various strategies of speed and current controllers [3-10]. The closed loop vector control technique is used for the PMSM to obtain the equivalent performance of a separately excited dc motor. Such technique is implemented using both current and speed controllers. A typical closed loop vector control scheme for the PMSM drive is shown in Fig. 1.

The most common strategies of current controllers can be classified as hysteresis and ramp comparator controllers [11]. Each scheme has its advantages and drawbacks with regard to insensitivity to parameters variations, accuracy, robustness and dynamic response over the entire speed range. The advantages of hysteresis current controllers lie in their simplicity and their providing fast responses and good accuracy, because they act quickly. However, the switching frequency may vary widely during the fundamental period,
resulting in irregular inverter operations. This is mainly due to the interference between the three-phase commutations. Thus, the actual current waveform is not determined by the hysteresis current control, the current slope may vary widely and current peaks may significantly exceed the limits of hysteresis bands. The ramp comparator controller has the advantages of limiting the maximum inverter switching frequency to the carrier triangular waveform frequency and producing well-defined harmonics. On the other hand, magnitude and phase errors in the line currents may be produced. Furthermore, multiple crossings of the ramp may become a serious problem when the current error time rate of change exceeds that of the ramp. A third strategy of current controllers is that of predictive controllers. The proposed controller is a combination of hysteresis and ramp controllers, this paper proposes a hybrid current controller. In particular, harmonic spectra of the stator current, obtained using a fast Fourier transform, are highlighted to measure the advantages and the simplicity of the proposed hybrid current controller. In particular, harmonic spectra of the stator current, obtained using a fast Fourier transform, are highlighted to measure the advantages and the simplicity of the proposed hybrid current controller. The ramp comparator scheme is used for low speed operations, the hysteresis current controller is used for high-speed operations and the ramp comparator controllers. Contrary to the hysteresis current control, the current slope may vary widely and the motor dynamics can be simply described by

\[
T_e = K_f I_q + \frac{K_v}{\Omega_f} (I_q - L_q) J I_q
\]  

and the motor dynamics can be simply described by

\[
\frac{J}{n_p} \frac{d\omega}{dt} + \omega = T_e - T_i
\]

Using the field orientation concept, assumption can be made that the \(d\)-axis current is controlled to be zero. The second term of equation (2) therefore becomes negligible. The reduced dynamic model of the PMSM is therefore given by the following set of equations.

\[
\frac{dI_d}{dt} = \frac{1}{L_d} V_d - R_1 I_d - \frac{\phi_f}{L_d} \omega,
\]

\[
\frac{J}{n_p} \frac{d\omega}{dt} = K_f I_q - \frac{f}{n_p} \omega - T_i
\]

The above system resolution provides the output variables \((I_p, \omega, \theta, I_x, T_e)\) of the PMSM block.

III. CURRENT CONTROLLER DESIGN

A. Hysteresis Current controller

In the vector control scheme, the current controller has direct influence on the drive performance and its design requires special considerations. The basic requirements for the current controllers are low harmonics to reduce losses, low torque pulsation, low noise in the motor, and fast response in order to provide high dynamic performance [20-21].

The logic operation of the voltage source inverter under current control is reported in table 1. There are eight switch combinations for the six switches of the inverter. The voltage vectors corresponding to the active states are shown in Fig. 2. The six commands \(V_1\) to \(V_6\) correspond to active voltage vectors; the remaining two \(V_7\) and \(V_8\) correspond to the zero voltage vectors [20, 22-23].

In the hysteresis current controller of Fig. 3, load currents \(I_x\) and \(I_y\) are respectively forced to follow reference currents \(I_{xref}\) and \(I_{yref}\) within a hysteresis band by the switching action of the inverter.

The upper and lower bounds of the hysteresis band are set for the motor current, and the hysteresis controller logic control can be described according to the following rules.

\[\text{Rule A:} \quad \text{For } I_{xref} > 0: \text{Th} 4 = 0, \quad \text{If } I_x > I_{xref} + \Delta I \quad \text{Then } \text{Th} 1 = 0, \quad \text{Else if } I_x < I_{xref} - \Delta I \quad \text{Then } \text{Th} 1 = 1, \quad \text{Else no change.}\]

\[\text{Rule B:} \quad \text{For } I_{xref} < 0: \text{Th} 1 = 0, \quad \text{If } I_x > I_{xref} + \Delta I \quad \text{Then } \text{Th} 4 = 1, \quad \text{Else if } I_x < I_{xref} - \Delta I \quad \text{Then } \text{Th} 4 = 0, \quad \text{Else no change.}\]
Table 1. VSI conduction modes.

<table>
<thead>
<tr>
<th>State Order</th>
<th>Leggs “Phase 1”</th>
<th>Leggs “Phase 2”</th>
<th>Leggs “Phase 3”</th>
<th>Operation Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vg</td>
<td>0 1 0 1 0 1</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Th5 Th6</td>
</tr>
<tr>
<td>V1</td>
<td>1 0 1 0 0 1</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Active</td>
</tr>
<tr>
<td>V2</td>
<td>0 1 1 0 0 1</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Active</td>
</tr>
<tr>
<td>V3</td>
<td>1 0 1 0 0 1</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Active</td>
</tr>
<tr>
<td>V4</td>
<td>0 1 0 1 1 0</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Active</td>
</tr>
<tr>
<td>V5</td>
<td>1 0 0 1 1 0</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Active</td>
</tr>
<tr>
<td>V6</td>
<td>0 1 1 0 1 0</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Active</td>
</tr>
<tr>
<td>V7</td>
<td>1 0 1 0 1 0</td>
<td>Th1 Th2</td>
<td>Th3 Th4</td>
<td>Freewheeling</td>
</tr>
</tbody>
</table>

B. Ramp Comparator Controller

The PMSM is generally driven by using current controlled VSI. In the ramp comparator scheme, the motor currents are sensed and compared to the reference currents, which are generated from the field-oriented controller. The ramp comparator controller is based on the following control logic rules.

**Rule A:** For $I_{\text{aref}} > 0$, if $I_a - V_{\text{tr}}> 0$ then $\text{Th4}=1$ else $\text{Th1}=1$.

**Rule B:** For $I_{\text{aref}} < 0$, if $I_a - V_{\text{tr}}> 0$ then $\text{Th1}=1$ else $\text{Th4}=1$.

In Figure 4, the error signals are compared to a triangular waveform to produce inverter constant frequency PWM drive signals. The switching frequency is limited to that of the triangular waveform and this represents the main advantage of the ramp comparator controller. However, inherent tracking amplitude and phase errors are the main drawbacks of this technique. Although good performances can be obtained for low and medium speeds, the amplitude and phase errors are introduced in the motor line currents. These amplitude and phase errors become unacceptable for high performance drive applications.

C. Hybrid Current Controller

In order to overcome the previously mentioned drawbacks of the hysteresis and ramp comparator controllers, a hybrid controller is proposed and implemented. The schematic diagram of the controller is shown in Fig. 5. The proposed hybrid current controller consists in the simultaneous use of the hysteresis and the ramp comparator controllers without a switching mode level between the hysteresis and ramp comparator modes.

The principle of the proposed hybrid current controller is based on the superposition of a high and a fixed frequency triangular signals to the current references. New current references are obtained; these are given by the following equations.
The new reference signals are compared to the actual currents. Error signals $e_a$, $e_b$, and $e_c$, then become the inputs to the hysteresis block control as illustrated by Fig. 5.

\begin{align}
I_{a\text{ref}} &= I_{a\text{ref}} + I_{tr} \\
I_{b\text{ref}} &= I_{b\text{ref}} + I_{tr} \\
I_{c\text{ref}} &= I_{c\text{ref}} + I_{tr}
\end{align}

\[ (5) \]

The upper and lower bounds of the hybrid current controller could then be defined using the new current references and the hysteresis band size $\Delta I$.

\begin{align}
I_{\text{upper}} &= I_{\text{ref}} + \Delta I \\
I_{\text{lower}} &= I_{\text{ref}} - \Delta I
\end{align}

\[ (6) \]

As illustrated by Fig. 6, the intersections of $I_a$ and $I_{\text{ref}}$ waveforms represent the switching instants. If a fixed frequency is required at the output, two rules must be respected. They are:

**Rule 1.** The switching ON of $\text{Th}1$ is obtained by the intersection of the descending part of the real current with the ascending part of the lower bound of the new current reference.

**Rule 2.** The switching OFF of $\text{Th}1$ is obtained by the intersection of the ascending part of the real current with the descending part of the upper band limit of the new current reference.

However, in case of a failure to comply with the above rules, two extreme cases will be obtained as depicted in Figs. 7 and 8. Theoretically speaking, the feasibility limits (Fig. 9) of the proposed hybrid current controller are defined by the minimum and maximum angles given by

\begin{align}
\alpha_{\text{min}} &\geq a \tan(2\Delta f_s) \\
\alpha_{\text{max}} &\leq a \tan(4 f_s (A_r + \Delta I))
\end{align}

\[ (8) \]
Hence, it is obvious that an exact design of the controller depends on the triangular waveform amplitude and frequency parameters noted respectively $A_n$ and $f_n$, the hysteresis band size $\Delta I$ and the stator time constants $\tau_d = L_d/R_s$ and $\tau_q = L_q/R_s$.

The purpose of the hybrid current controller is to impose a fixed switching frequency to the inverter. As a result, the following expression is always true.

$$\max(I_a) - I_{\text{aref}} \leq A_n \tag{9}$$

At the upper and lower limits, DC link voltage $E$ may reset the switching frequency.

IV. SIMULATION RESULTS

The control algorithms of the hysteresis, the ramp comparator and the proposed hybrid controller, for the PMSM drive system, have been developed and implemented using a Matlab/Simulink programming environment. Simulations were carried on a 0.9-kW PMSM whose ratings and parameters are presented in the appendix.

Figure 10 shows the performance of the hybrid current controller for a 150-rad/sec speed command at a rated load condition ($T_L = 3$-N-m). It is worth mentioning that the motor speed accurately tracks the command with no overshoot. During the start up period, the developed torque equals the motor maximum capability. This ensures that the PMSM runs up in the shortest time possible and the developed torque decreases in order to satisfy the applied load torque.

Figure 11 shows the steady state line current and the reference current at various speed references, with a triangular carrier frequency of 1.5-kHz. The instantaneous value of the real current is lower than the reference current. The actual current remains at the inferior part of the triangular waveform of the new reference current.

At a given speed, the error between $I_a$ and $I_{\text{aref}}$ increases as the instantaneous value of the real current increases near the peak value of $I_{\text{aref}}$. In the neighborhood of the zero crossing-point, the difference is small. This is exactly in agreement with the mixed band hysteresis current controller that combines the fixed and the sinusoidal band controllers [23]. In addition, during a single period $T_r$ of the triangular waveform, four changes of current $dI/dt$ are observed. Two changes are caused by phase $A$. The other two are caused by the switching of $B$ and $C$ phases.

Figure 12 shows that phase voltage $V_m$ waveform has the same shape as the one obtained by the ramp comparator controller with five levels: 0, $\pm E/3$ and $\pm 2E/3$. For $L_s \geq 20$, the $V_m$ corresponding values are obtained by the following applied vectors: $V_f(1,0,0), V_g(1,1,0), V_d(1,0,1)$, and $V_e(0,0,0)$.

In case of the fixed band hysteresis controller, even if the regulation requires increased current, it can decrease due to the controllers’ interaction. Any voltage vectors $V_6$ to $V_7$ may be applied. This leads to an irregular waveform of the voltage and a variable switching frequency of the inverter as depicted in Fig. 13. As a result, the harmonics order can reach 80. Figure 14 shows the corresponding harmonic spectrum at a rated load and a rated speed. It is observed that in the case of the hybrid current controller, the harmonic distortion is low as compared to the fixed band hysteresis controller.

The proposed hybrid controller then shows a compromise between the harmonic distortion and the inverter switching frequency.
It has been shown in recent literature that good performance with a high-speed drive may be achieved by using the hysteresis current controller, whereas with a low-speed drive the ramp comparator controller is the most appropriate one. To take advantage of both controllers, a new hybrid current controller has been proposed and validated by simulations. Detailed analysis of various current controllers for a PMSM drive has been presented.

Comparisons through simulations confirm that the proposed hybrid current controller gives better performance and has the advantage of conceptual simplicity.

In contrast to the classical current control schemes, the following features characterize the proposed hybrid current controller:

- The switching frequency is kept almost constant.
- Regular voltage waveform is given by a limited number of voltage vectors.
- Exact agreement with a mixed band hysteresis controller, defined as a combination of fixed and sinusoidal band hysteresis controllers [24].
- Notable reduction of the distortion components that are concentrated around the near-switching frequency.

**APPENDIX**

**RATED DATA OF THE SIMULATED PMSM**

<table>
<thead>
<tr>
<th>Rated values</th>
<th>Power</th>
<th>Frequency</th>
<th>Voltage (Δ/Y)</th>
<th>Speed</th>
<th>Torque</th>
<th>Pole pair (n_p)</th>
<th>Rated parameters</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9 kW</td>
<td>50 Hz</td>
<td>220 V</td>
<td>1500 rpm</td>
<td>3 N-m</td>
<td>2</td>
<td>ϕ_f</td>
<td>1.1 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R_s</td>
<td>1.5 Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L_d</td>
<td>0.0349 H</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L_q</td>
<td>0.0627 H</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>J</td>
<td>0.003 kg·m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>f</td>
<td>0.000008 N·m·s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( f_c )</td>
<td>1.5 kHz</td>
</tr>
</tbody>
</table>

**REFERENCES**


Mohamed KADJOUDJ was born in Batna, Algeria, in 1964. He received the B.Sc. and M.Sc. degrees both in Electrical Engineering, from the University of Batna, Algeria, in 1988 and 1992 respectively. After graduation, he joined the University of Batna, Algeria, where he is a Teaching Assistant at the Electrical Engineering Institute. He is currently working towards a Ph.D. thesis on the intelligent control of permanent magnet synchronous motors.

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