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Scalar Control of a New Phase-Decoupling Permanent Magnet Synchronous Motor for Servo Application

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Abstract—This paper presents a new scalar-controlled phase-decoupling permanent magnet synchronous motor (PD-PMSM) which takes the advantages of smooth torque, fast response and good controllability for servo applications. Because of the PD nature, the proposed scalar control strategy can simply adjust the phase current amplitude and its angle with respect to the back EMF to achieve direct torque control. Experimental results are given to verify the advantages of the proposed scalar-controlled PD-PMSM.

Keywords—PD-PMSM; scalar control; current control

I. INTRODUCTION

For high-performance servo application, the candidate electric machine needs to possess high efficiency, high power density and high controllability. In the past, dc motors were usually employed in high-performance applications for their simple controllability and good dynamic capability. However, they suffer from many drawbacks due to the use of brushes. Early attempts to replace the dc motor with brushless motor encountered the problem of cost, efficiency and controllability. With the invention of neodymium-iron-boron (Nd-Fe-B) magnets, the development of permanent magnets brushless AC (PMAC) motors has taken on an accelerated pace. Owing to high energy PMs, PMAC motors can offer higher efficiency, power factor, power density and better dynamic performance than induction motors without sacrificing reliability. Therefore, PMAC motors are playing an increasingly important role in high-performance servo applications. Those viable types of PM brushless motors are the PM synchronous motor (PMSM) [1], PM brushless DC motor (PMBDCM) [2], doubly salient PM motor (DSPM) [3], and PM hybrid motor (PMHM) [4]. Among them, the PMSM takes the definite advantage of smoother torque than its counterparts.

PMSM fed from current regulated inverters are usually used in those applications where rapid torque response and high performance operation are needed. For surface-mounted PMSM ($L_d = L_q$), the current control structure including two or three analog independent current loops is usually used in industrial scheme for its simple structure and fast dynamic response. However, as for interior PMSM (IPMSM) ($L_d > L_q$) which can offer a high-efficiency drive by utilizing the reluctance torque, an independent current loops structure is not effective for it to realize high performance operation with fast dynamic response [5], due to the presence of variable parameters and significant coupling. In that case, similar to the control of induction motor, vector control based on coordinate transformation has to be employed [6]. However, vector control needs intensive computation for coordinate transformation. Moreover, due to the high sensitivity of vector control on machine parameters, the parameter variations during operation may deteriorate the desired performance [7]. Recently, the nature of decoupling has been extended to machine design [8]. Namely, the IPMSM is designed to decouple the flux linkage between phases, so-called phase-decoupling (PD). Thus, vector control is no longer necessary.

The purpose of this paper is to present a novel scalar-controlled PD IPMSM motor drive for servo application. Based on the inherent PD nature, mutual inductance between each phase is effectively eliminated. Hence, independent current control of each phase can be accomplished. A simple scalar control of the phase current amplitude and its angle with respect to the back EMF can be devised for direct torque control. As a result, there is no need to perform the complicated coordinate transformation for vector control. Experimental results will be given to verify that the proposed scalar-controlled PD-PMSM not only offers smooth torque and fast response, but also wide constant-power operating range for servo applications.

II. MOTOR DESIGN & ANALYSIS

The schematic configuration of the proposed phase-decoupling IPMSM is shown in Fig.1, which is a 3-phase 10-pole motor. In order to improve its controllability, dynamic performance and torque smoothness to satisfy the stringent servo requirements, the proposed motor features the flux shaping air gap, the flux-focusing PM rotor, and the phase-decoupling stator windings. As the former two approaches have been generalized in our recent work [8], this paper will focus on the more details of the phase-decoupling stator windings design.

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Differing from the conventional PMSMs, the slot number of the proposed IPMSM should be governed by (1) so as to make the flux paths of different phases symmetric.

\[ Z = 2mk \]  

(1)

where \( m \) is the motor phase number and \( k \) is an integer.

In order to minimize the cogging torque, fractional-slot winding is adopted. The slot-pole match is selected to be:

\[ Z = 2p \pm 2 \]  

(2)

III. MATHEMATICAL MODEL OF PD-PMSM

As for conventional IPMSM which is described with strong decoupling and variable parameter equations as (1), vector control based on coordinate transformation has to be employed to accomplish linear decoupling control.
where \( v, i, e, R, L \) and \( M \) are the voltages, currents, back EMFs, and mutual inductance of different phases, respectively. Because of the PD nature, the voltage equation of the proposed IPMSM is simplified to be:

\[
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix} = \begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
L_{AA} & M_{AB} & M_{AC} \\
M_{BA} & L_{BB} & M_{BC} \\
M_{CA} & M_{CB} & L_{CC}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}
\]  

(3)

The third term on the left side of (6) is generated due to 2nd-order harmonic component of the self inductance. Fortunately, this term whose frequency is the triple of primary frequency will not induce current in the motor drive without neural line. It can be regarded as the load-side neural point voltage. Hence, the phase voltage equation of the PD-PMSM can be reduced to:

\[
v_p = R_p I_a + \omega_m I_a \sin(\omega t - \delta) + \frac{X_m}{2} I_a \cos(\omega t - \frac{\pi}{2} + \gamma) + E_p
\]

(7)

where \( X_m = X_{a0} - 0.5 X_2 \), \( \gamma = \varphi - \delta \).

Therefore, the whole relations between voltage, current and back EMF for each phase can be plotted on a complex plane as shown in Fig.6. Rearranging equation (5), the equation (9) below can be obtained:

\[
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix} = \begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
L_{AA} & 0 & 0 \\
0 & L_{BB} & 0 \\
0 & 0 & L_{CC}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
l_{pp}
\end{bmatrix} + \omega_m \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
l_{pp}
\end{bmatrix} + \omega_m \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

(8)

\[
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix} = \begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
L_{AA} & M_{AB} & M_{AC} \\
M_{BA} & L_{BB} & M_{BC} \\
M_{CA} & M_{CB} & L_{CC}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
l_{pp}
\end{bmatrix} + \omega_m \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
l_{pp}
\end{bmatrix} + \omega_m \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

Figure 6.  Scalar control operation.
where $V_a$, $I_a$ and $V_r$, $I_r$ are active and reactive component of $V_p$, $I_p$, and $X_a = X_0 - 0.5X_2$, $X_r = X_0 + 0.5X_2$.

Based on (8), active and passive power for each phase can be expressed as:

\[
P_p = U_p^2 I_p^2 \cos \varphi = R_p I_p^2 + E_p I_p \cos \gamma + \frac{1}{2} X_p I_p^2 \sin 2\gamma \quad (10)
\]

\[
Q_p = U_p^2 I_p \sin \varphi = X_p I_p^2 + X_2 \sin^2 \gamma \cdot I_p^2 + E_p I_p \sin \gamma \quad (11)
\]
According to (10), the torque equation for each phase can be easily expressed as:

\[ T_s = \frac{P}{\omega_s} (E_p I_p \cos \gamma + \frac{1}{2} X_p I_p^2 \sin 2\gamma) \]  \hspace{1cm} (12)

where \( p \) is the number of pole-pairs, \( \gamma \) is the phase shift between \( E_p \) and \( I_p \).

Equation (7) and (12) make up the mathematical model for PD-PMSM.

IV. PRINCIPAL OF SCALAR-CONTROL

Because of the PD nature, the proposed IPMSM presents different operation principal from conventional PMSMs. Its spatial magnetic-field is no longer circumrotating. Actually, it is a combination of three independent sinusoidally vibrating magnetic fields. Each single-phase magnetic field interacts with permanent magnetic field and produces the single-phase sinusoidally vibrating torque independently as seen in (12). Thus, the proposed IPMSM can be treated as a special structure with three single-phase motors, while the output torque can be regarded as the sum of the torque of the three motors.

As it can be seen as in (4) and (7), the motor can be described by three independent equations, which offers a definite advantage that the current of each phase can be independently controlled. Although the problem of the variable parameters and non-linearity still exist, they can be easily overcome by high-speed current-regulation techniques. Hence, a simple scalar control of phase current amplitude and its angle with respect to the back EMF can be devised for direct torque control. Complex coordinate transformation and computation are no longer necessary. Fig.6 illustrates how to control the phase current and hence the torque. In the region of constant torque operation the current is controlled in the same phase with rotational EMF for each motor phase as shown in Fig.6. The output torque can be simply controlled by adjusting the amplitude of the current with \( \gamma = 0 \). At this time, the output torque of the PD-PMSM can be expressed as:

\[ T_s = \frac{3p}{\omega_s} E_p I_p \]  \hspace{1cm} (13)
If high-speed operation above the rated speed is needed, advanced conduction technique can be employed with $\gamma \neq 0$ so that phase current conducts when the rotational EMF is still negative. By employing reactive voltage $I_r X_r$, produced by the component of phase current $I_r$ and source voltage to oppose the EMF as shown in Fig.6, thus constant power operation can be accomplished and maintained in high-speed region. Due to the contribution by the reluctance torque, the output torque can be expressed as:

$$T_e = \frac{3p}{\omega_s} (E_p I_p \cos \gamma + X_r I_p^2 \sin 2\gamma)$$

(14)

V. CONTROL SYSTEM & IMPLEMENTATION

Based on a low-cost microprocessor, a dual closed-loop speed and current feedback control system is developed for the proposed PD-PMSM. As compared with the vector control of conventional IPMSM, the control is much simpler because there is no vector transformation. Fig.7 shows the block diagram of the control system, and the control process can be explained by Fig.8.

When the speed reference $\omega^*$ is set, the motor begins starting and the speed feedback is increasing gradually. The difference between $\omega^*$ and speed feedback $\omega$ is inputted into the speed proportional-integral regulator, where $K_p$, $K_i$ and $\tau$ are the corresponding proportional constant and time constant. The amplified output $i^*$ serves as an amplitude reference of phase current for the inner current control loops.

In order to produce the sinusoidal current commands and control the phase current finely, the high-resolution rotor position information $\theta_r$ is sensed from an optical encoder fixed on the motor axis. The amplitude reference $i^*$ and rotor position $\theta_r$ are transformed to the sinusoidal current commands $i^*_a$, $i^*_b$, $i^*_c$ through the read-only memory tables. Then, they are output through multiplying D/A converters. The phase current feedbacks are compared with $i_a^*$, $i_b^*$, $i_c^*$ respectively and their differences are inputted into the current controllers. The current regulated inverter drives the phase-decoupling IPMSM so that the instantaneous phase currents can follow their reference values well.

The three independent current controllers are the key of scalar control system. The steady and dynamic performances of
the current controllers directly determine the performance of motor output torque. Three high-performance delta-modulated current controllers (DMCC) for each phase have been developed. The DMCC is basically a non-linear system containing sampler, zero-order holder and ideal relay units. The current command is compared with the current feedback at any moment, but the comparison result is sampled only at the interval of every control cycle. Based on the sample results, DMCC controls the on/off state of the responding switches on the phase leg so that the phase current can trace the reference signal [9]. Thus, DMCC can overcome the disadvantage of unstable switching frequency existing in most conventional hysteresis current controllers. In order to improve the dynamic response of the current regulator, the DMCC is realized with analogue circuits. The fast MOSFET inverter can work at the maximum switching frequency up to 40kHz, ensuring an excellent current control performance with minimum harmonic contents.

VI. EXPERIMENT RESULTS

Based on the newly design PD-PMSM (see Fig.9, 10 and Table 1) and the proposed scalar control strategy, the whole system is prototyped for experimental verification. Fig. 11, 13 and Fig. 12, 14 show the measured waveforms and harmonic spectra of the EMF and current, respectively. It can be found that they are very sinusoidal, hence confirming the torque smoothness. Fig. 15, 16 show the measured phase and line voltage. Moreover, Fig.17 and 18 show the measured speed and current responses at starting and sudden load change, respectively. It can be seen that the rise-up time is very short with minimum overshoot during starting, while the speed regulation is very good with minimum undershoot during sudden load change, hence verifying the fast response and good controllability. Fig.20, 21 illustrate the measured current and its harmonic spectra at the constant power operation with $\gamma = 50^\circ$. Finally, the simulated and measured torque-speed capabilities are shown in Fig.22, which confirms that the scalar-controlled PD-PMSM offers a wide range of constant-power operation. The agreement confirms that the proposed motor can offer constant torque operation at the rated torque of 3Nm and constant-power operation up to 2600rpm. There are some discrepancies at speeds beyond 2300rpm, which are mainly due to the increasing significance of nonlinear windage and frictional torques at high speeds.
### VII. Conclusion

This paper presents and implements a new PD-PMSM motor drive for servo application. Based on the PD nature of the proposed IPMSM, a novel scalar torque control strategy has been put forward, which enables the control system to exempt from coordinate transformation for vector control. A digital speed controller based on low-cost DSP combined with high-performance current controller has been developed to operate the prototype motor drive. The results show that the proposed scalar-controlled PD-PMSM not only offers smooth torque and fast response, but also wide constant-power operating range for servo applications.

### References


### Table I. Motor Specifications.

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<th>Data</th>
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<tr>
<td>Rated voltage</td>
<td>40 V</td>
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<tr>
<td>Rated torque</td>
<td>3 Nm</td>
</tr>
<tr>
<td>Rated current</td>
<td>10 A</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1000 rpm</td>
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**Stator**

<table>
<thead>
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<td>No. of phases</td>
<td>3</td>
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<tr>
<td>Outside diameter</td>
<td>100 mm</td>
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<td>Inside diameter</td>
<td>59.6 mm</td>
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<td>Axial length</td>
<td>60 mm</td>
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<td>No. of slots</td>
<td>12</td>
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<td>Winding type</td>
<td>Single layer</td>
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<td>No. of coils</td>
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<td>Conductor size</td>
<td>8 × 0.78mm</td>
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<td>Coil length per phase</td>
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<td>Resistance per phase</td>
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<tr>
<td>Average self inductance per phase</td>
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<tr>
<td>Average mutual inductance per phase</td>
<td>0.037 mH</td>
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**Rotor**

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<td>No. of poles</td>
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<td>Outside diameter</td>
<td>58.9 mm</td>
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<td>Inside diameter</td>
<td>18 mm</td>
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<td>Main pole magnet dimensions</td>
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<td>Auxiliary pole magnet material</td>
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<td>Auxiliary pole magnet dimensions</td>
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<td>1.1T</td>
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<tr>
<td>Magnet coercive</td>
<td>676 kA/m</td>
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