Multi-dimension SVPWM-based sensorless control of 7-phase PMSM drives

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ABSTRACT

A new control technique for the 7-phase permanent magnet synchronous machine (PMSM) when a failure in the speed sensor is introduced. This will make the whole drive system more robust and at the same time reduce the cost. The speed and the position of the shaft of the motor are obtained by tracking the saturation saliency of the 7-phase motor when a failure in speed sensor is occurred. The proposed saliency-tracking algorithm is based on measuring the derivative of the stator currents of the 7-phase motor after the switching of the insulated gate bipolar transistor (IGBT) of the 7-phase inverter due to the implementation of the multi-dimension space vector pulse width modulation (SVPWM). This modulation technique is used in the 7-phase drives to suppress the 3rd and 5th harmonics. Simulation results show that the 7-phase motor drive could track the reference speed at different load conditions when a failure in the speed sensor is occurred without compromising the performance.

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1. INTRODUCTION

Multi-phase motors have gained significant interest in research in the new century [1], [2]. The benefits of these machines are what have sparked this interest. These benefits including high power, low torque ripple, and most importantly, good performance under fault conditions. The space vector pulse width modulation (SVPWM) technique can be utilized in the multi-phase drive system too with some extensions to consider the increased number of the switching vectors and the existence of 3rd, 5th and other harmonics. These SVPWM techniques are called multi-dimension SVPWM that will produce a sinusoidal output voltage by synthesizing voltage vectors in several d-q subspaces [3]–[9].

Industrial drive systems predominantly use speed-controlled systems. These speed-controlled drives are based on vector control theory where the d-q components of the stator current are acquired using the rotor position determined by optical encoders or resolvers. However, utilizing such sensors will decrease the overall reliability of the drive system. Therefore, much research is directed toward “sensorless” or “encoderless” vector control where the rotor position is obtained without using the speed sensors [10]–[15].

Speed control of the 5-phase motor when a failure in the speed sensor is occurred has been researched in many papers published in the last decade. Some of these papers used were model-based techniques. Others used the direct-torque control method to obtain a speed-controlled the 5-phase motor. And few papers used a high-frequency injection method to get the speed and position of the 5-phase motor [16]–[20]. In the past
couple of years, a few papers have been published in the field of the model-based sensorless control of the 7-phase motor [21]–[27] In this year, a new paper has been published in the field of sensorless control of the 7-phase motor based on voltage excitation when a failure in the speed sensor is occurred [28]. The paper has compared three techniques to track the saliency of the 7-phase drive in terms of the current distortion. Although the three algorithms presented in that paper and the algorithm presented in this paper are using the same technique to get the shaft speed and position when a failure in the speed sensor is occurred, there are two major differences. The first one is the algorithm presented in this paper is much easier to be implemented than the algorithms presented in that paper. The second difference is that the algorithm presented in this paper to track the saturation saliency isn’t needing any offline commissioning to achieve a closed-loop sensorless speed control while the algorithms presented in that paper need a lot of offline commissioning effort. This is because the DC offset of all the saturation saliency position scalars is equal in the new algorithm in all sectors while the dc offset of the position scalars is different in the same sector and between sectors. Finally, the new algorithm can be applied to acquire the saliency position in the 7-phase motor drives when one phase of the motor is lost due to the open-circuit failure while the algorithms published in [28] can’t.

This research is presenting a speed control of the 7-phase drive based on the voltage excitation method when a failure in speed sensor is occurred. This will make the whole drive system more robust and reduce the cost. The voltage excitation technique is a technique used to get shaft speed and position through tracking the saliency. The tracking of the saliency is relying on measuring the current derivative of the stator motor currents when the insulated gate bipolar transistor (IGBT) of the inverter are switched on and off resulted by implementing the multi-dimension SVPWM used in a 7-phase motor.

2. OPERATION OF THE 7-PHASE PMSM WITHOUT FAUL

2.1. Modelling the 7-phase PMSM

Figure 1 demonstrates the 7-phase permanent magnet synchronous machine (PMSM) drive topology. The 7-phase motor is fed from the 7-phase inverter. The IGBTs in the 7-phase inverter will be switched according to the pulse width modulation (PWM) signals generated using the multi-dimension SVPWM technique. The details of the multi-dimension SVPWM will be discussed in section 2.2. The model of the 7-phase drive is given in (1)-(3).

\[
[V_s] = r_s * [I_s] + q * [\phi_s] \tag{1}
\]

Where \([V_s] = [V_{sA}, V_{sB}, V_{sC}, V_{sD}, V_{sE}, V_{sF}, V_{sG}]^T\) are the stator applied voltages, \(r_s\) is the stator resistance, \([I_s] = [i_{sA}, i_{sB}, i_{sC}, i_{sD}, i_{sE}, i_{sF}, i_{sG}]^T\) are the stator currents, voltages, \(q = \frac{d}{dt}\) and \([\phi_s] = [\phi_{sA}, \phi_{sB}, \phi_{sC}, \phi_{sD}, \phi_{sE}, \phi_{sF}, \phi_{sG}]^T\) are the stator linkage fluxes. The stator linkage fluxes can be expressed as in (2).

\[
[\phi_s] = L_s * [I_s] + \varphi_M \tag{2}
\]
\[
\varphi_M = \hat{L}_m \times \begin{bmatrix}
    \cos(\theta_R) \\
    \cos(\theta_R - 2\theta_x) \\
    \cos(\theta_R - 4\theta_x) \\
    \cos(\theta_R - 6\theta_x) \\
    \cos(\theta_R - 8\theta_x) \\
    \cos(\theta_R - 10\theta_x) \\
    \cos(\theta_R - 12\theta_x)
\end{bmatrix}
\]

Where \( L_s \) is the stator inductances matrix, \( \hat{L}_m \) is the peak permanent magnet flux linkage, \( \theta_R \) is the rotor position, and \( \theta_x \) is \( \pi/7 \). The parameters of the motor that is used in this research are as following: rated voltage=400 V, rated speed=1500 rpm, rated torque=12 N.m, rated power=2.15 kW, \( k_t=1.2 \) N.m/A, \( k_e=147\)v/Krpm, \( \text{inertia}=20\)kg/cm², \( R(\text{ph}-\text{ph})=4\) \( \Omega \), and \( L(\text{ph}-\text{ph})=29.8\) mH.

### 2.2. Multi-dimension SVPWM technique

#### 2.2.1. Space vectors distribution

It is well known that if the output voltage of the inverter has any 3rd or 5th harmonics, then this will produce a large 3rd and 5th harmonics in the 7-phase motor currents. The reason for that is these harmonics will be limited by the stator impedances only [3]–[8] as no rotating MMF is produced. Therefore, it is crucial to remove the third and fifth harmonics from the inverter's output voltage in a 7-phase motor drive. This can be achieved by extracting these components and then controlling them to be zero. To extract the 3rd and 5th harmonics from the fundamental component, the reference voltage (\( V_{\text{ref}} \)) is needed to be decoupled into three planes. The first plan is rotating at a synchronous speed called the \( \alpha_1-\beta_1 \) plane to extract the fundamental \( V_{\text{ref}} \). The second one is rotating 3 times faster than the first plane called the \( \alpha_3-\beta_3 \) plane to extract the 3rd harmonic. The final one is rotating 5 times faster than the first plane called the \( \alpha_5-\beta_5 \) plane to extract the 5th harmonic component of the \( V_{\text{ref}} \) using the transformation given in (4)-(6).

\[
\begin{bmatrix}
\alpha_1 \\
\beta_1 \\
\alpha_3 \\
\beta_3 \\
\alpha_5 \\
\beta_5
\end{bmatrix} = \begin{bmatrix}
A \\
B \\
C \\
D \\
E \\
F \\
G
\end{bmatrix}
\]

\[
\begin{bmatrix}
A \\
B \\
C \\
D \\
E \\
F \\
G
\end{bmatrix} = \begin{bmatrix}
\alpha_1 \\
\beta_1 \\
\alpha_3 \\
\beta_3 \\
\alpha_5 \\
\beta_5
\end{bmatrix}
\]

where

\[
G = \frac{1}{2} \begin{bmatrix}
1 & \cos(2\theta_x) & \cos(4\theta_x) & \cos(6\theta_x) & \cos(8\theta_x) & \cos(10\theta_x) & \cos(12\theta_x) \\
0 & \sin(2\theta_x) & \sin(4\theta_x) & \sin(6\theta_x) & \sin(8\theta_x) & \sin(10\theta_x) & \sin(12\theta_x) \\
1 & \cos(6\theta_x) & \cos(12\theta_x) & \cos(18\theta_x) & \cos(24\theta_x) & \cos(30\theta_x) & \cos(36\theta_x) \\
0 & \sin(6\theta_x) & \sin(12\theta_x) & \sin(18\theta_x) & \sin(24\theta_x) & \sin(30\theta_x) & \sin(36\theta_x) \\
1 & \cos(10\theta_x) & \cos(20\theta_x) & \cos(30\theta_x) & \cos(40\theta_x) & \cos(50\theta_x) & \cos(60\theta_x) \\
0 & \sin(10\theta_x) & \sin(20\theta_x) & \sin(30\theta_x) & \sin(40\theta_x) & \sin(50\theta_x) & \sin(60\theta_x)
\end{bmatrix}
\]

By utilizing the zero-sequence voltage, the vectors \( V_s1 \), \( V_s3 \), and \( V_s5 \) in the \( \alpha_1-\beta_1 \), \( \alpha_3-\beta_3 \), and \( \alpha_5-\beta_5 \) planes respectively can be deduced directly using (7).

\[
\begin{bmatrix}
V_{s1} \\
V_{s3} \\
V_{s5}
\end{bmatrix} = \frac{2}{7} \times V_{dc} \begin{bmatrix}
1 & e^{2j\theta_x} & e^{4j\theta_x} & e^{6j\theta_x} & e^{8j\theta_x} & e^{10j\theta_x} & e^{12j\theta_x} \\
e^{2jx2\theta_x} & e^{4jx2\theta_x} & e^{6jx2\theta_x} & e^{8jx2\theta_x} & e^{10jx2\theta_x} & e^{12jx2\theta_x} & e^{14jx2\theta_x} \\
e^{5jx2\theta_x} & e^{5jx4\theta_x} & e^{5jx6\theta_x} & e^{5jx8\theta_x} & e^{5jx10\theta_x} & e^{5jx12\theta_x} & e^{5jx14\theta_x}
\end{bmatrix} \begin{bmatrix}
S_A \\
S_B \\
S_C \\
S_D \\
S_E \\
S_F \\
S_G
\end{bmatrix}
\]

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Where $V_{DC}$ is the DC link voltage, and $S_A, S_B, S_C, S_D, S_E$, and $S_G$ are the pulses to trigger the upper IGBTs of the 7-phase inverter. Based in (7), a 128-switching vector can be generated and distributed in space as shown in Figures 2, 3(a) and (b). The amplitude of the vectors U1-U7 are given in Table 1.

![Figure 2. Voltage vector space distribution in $\alpha_1$-$\beta_1$ plan](image1.png)

![Figure 3. Voltage vector space distribution in (a) $\alpha_3$-$\beta_3$ plan and (b) $\alpha_5$-$\beta_5$ plan](image2.png)

**Table 1. Switching vector amplitudes**

<table>
<thead>
<tr>
<th>Vector group name</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>U4</th>
<th>U5</th>
<th>U6</th>
<th>U7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>$0.127 \times V_{DC}$</td>
<td>$0.159 \times V_{DC}$</td>
<td>$0.229 \times V_{DC}$</td>
<td>$0.286 \times V_{DC}$</td>
<td>$0.356 \times V_{DC}$</td>
<td>$0.515 \times V_{DC}$</td>
<td>$0.642 \times V_{DC}$</td>
</tr>
</tbody>
</table>

### 2.2.2. Switching vector selection and dwell time calculation

Theoretically, the seven vector groups (U1, U2, U3, U4, U5, U6, and U7) can be utilized to synthesize the $V_{\text{ref}}$. But, only the adjacent vectors U4, U6, and U7 are utilized to generate the $V_{\text{ref}}$ in each sector practically. This is related to the non-continuity and the modest amplitude of the vectors U1, U2, U3, and U5. For instance, the six active vectors V1 (1000000), V3 (1100000), V67 (1100001), V71 (1110001),
V103(1110011), V111(1111011) in addition to the two null vectors V0(0000000), and V127(1111011) are utilized to generate the $V_{ref}$ in sector 1 in $\alpha_1$-$\beta_1$, $\alpha_3$-$\beta_3$, and $\alpha_5$-$\beta_5$ planes respectively as illustrated in Figures 4(a)-(c) respectively. The associated SVPWM waveform is depicted in Figure 4(d). The time of application of each vector is derived as (8).

$$
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6
\end{bmatrix} = T_s \times [T^{-1}]
\begin{bmatrix}
V_{ref_{\alpha_1}} \\
V_{ref_{\beta_1}} \\
V_{ref_{\alpha_3}} \\
V_{ref_{\beta_3}} \\
V_{ref_{\alpha_5}} \\
V_{ref_{\beta_5}}
\end{bmatrix}
$$

(8)

$$
T = \begin{bmatrix}
U4 & U6\cos(\theta_x) & U7 & U7\cos(\theta_x) & U6 & U4\cos(\theta_x) \\
0 & U6\sin(\theta_x) & 0 & U7\sin(\theta_x) & 0 & U4\sin(\theta_x) \\
U4 & U1\cos(3\theta_x) & -U3 & U3\cos(10\theta_x) & U1 & U4\cos(3\theta_x) \\
0 & U1\sin(3\theta_x) & 0 & U3\sin(10\theta_x) & 0 & U4\sin(3\theta_x) \\
U4 & U5\cos(12\theta_x) & U2 & U2\cos(5\theta_x) & -U5 & U4\cos(5\theta_x) \\
0 & U5\sin(12\theta_x) & 0 & U2\sin(5\theta_x) & 0 & U4\sin(5\theta_x)
\end{bmatrix}
$$

(9)

where

$$
T_0 = T_2 - T_1 - T_2 - T_3 - T_4 - T_5 - T_6
$$

(10)

Figure 4. Multi-dimension SVPWM vector synthesis in; (a) $\alpha_1$ – $\beta_1$ plan, (b) $\alpha_3$ – $\beta_3$ plan, (c) $\alpha_5$ – $\beta_5$ plan, and (d) NSV-SVPWM waveform

The algorithm to implement the multi-dimension SVPWM in terms of calculating the dwell time and the switching sequence in any sector k is given in the flow chart shown in Figure 5. Table 2 in addition to $w_1$ and $w_2$ are shown below.
Table 2. switching sequence in different sectors using multi-dimension SVPWM

<table>
<thead>
<tr>
<th>Sector no</th>
<th>H0</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
<th>H5</th>
<th>H6</th>
<th>H7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V0</td>
<td>V1</td>
<td>V3</td>
<td>V6</td>
<td>V7</td>
<td>V0</td>
<td>V0</td>
<td>V1</td>
</tr>
<tr>
<td>2</td>
<td>V0</td>
<td>V2</td>
<td>V3</td>
<td>V7</td>
<td>V1</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>3</td>
<td>V0</td>
<td>V4</td>
<td>V6</td>
<td>V7</td>
<td>V1</td>
<td>V4</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>4</td>
<td>V0</td>
<td>V4</td>
<td>V6</td>
<td>V7</td>
<td>V1</td>
<td>V4</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>5</td>
<td>V0</td>
<td>V4</td>
<td>V6</td>
<td>V7</td>
<td>V1</td>
<td>V4</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>6</td>
<td>V0</td>
<td>V6</td>
<td>V8</td>
<td>V1</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>7</td>
<td>V0</td>
<td>V8</td>
<td>V2</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>8</td>
<td>V0</td>
<td>V16</td>
<td>V4</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>9</td>
<td>V0</td>
<td>V16</td>
<td>V4</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>10</td>
<td>V0</td>
<td>V32</td>
<td>V4</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>11</td>
<td>V0</td>
<td>V32</td>
<td>V4</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>12</td>
<td>V0</td>
<td>V64</td>
<td>V6</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>13</td>
<td>V0</td>
<td>V64</td>
<td>V6</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
<tr>
<td>14</td>
<td>V0</td>
<td>V64</td>
<td>V6</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V0</td>
<td>V2</td>
</tr>
</tbody>
</table>

2.3. Control of the 7-phase drive without fault

Figure 6 demonstrates the schematic of the vector-control structure that was utilized to achieve a speed-controlled of the 7-phase PMSM drive under healthy operating conditions. It can be noticed from the
figure that rotor position and speed are obtained by the encoder. Moreover, it can be noticed that both the 3rd harmonic and the 5th harmonic components were regulated to zero through putting \(id_3\text{\_ref}, iq_3\text{\_ref}, id_5\text{\_ref,}\) and \(iq_5\text{\_ref}\) to zero. The whole control structure illustrated in Figure 6 was implemented using the SABER simulation package and the results are shown in Figure 7. The speed of the motor was regulated at 180 rpm at half load. The stator currents were symmetrical and shifted by \((\pi/7)\). Moreover, the spectrum of one phase of the motor shows that third 3rd and 5th harmonics were not found as they are regulated to zero. At \(t=1.5\) s, the reference speed of the motor was changed to zero rpm. Then at \(t=3\) s, the reference speed of the motor was changed back to 180 rpm. In both cases, the system drive has a very good dynamic and transient response.

![Figure 6. 7-phase drive control structure using multi-dimension SVPWM before speed sensor failure](image)

![Figure 7. Speed control of the 7- phase motor without faults](image)
3. CONTROL OF THE 7-PHASE PMSM WHEN A FAILURE IN THE SPEED SENSOR IS OCCURRED

3.1. Salency tracking algorithm

The stator inductance matrix \( L_s \) in (2) was modeled to include the effect of the saturation saliency of main flux and hence the term \( (2r) \) was used. Hence, the saliency position and the shaft position can be identified by metering the derivative of the stator currents when the IGBTs are switched on and off in one PWM waveform. Figure 8(a) shows multi-dimension SVPWM vector synthesis and Figure 8(b) shows the PWM waveform for a 7-phase inverter when the V_ref exists in sector 1. Also, the figure shows the time instants for metering derivative of the stator current when the inverter IGBTs are switched. The stator circuit when the vectors (H0-H7) i.e (V0, V1, V3, V67, V71, V103, V111, and V127) are applied are shown in Figures 9(a)-(g) respectively.

Using the dynamic equivalent circuit shown in Figure 9(a), (11) holds true.

\[
[0] = r_s \* [i_{sA}(V^0)] + [l_{qA} \* q(i_{qA}(V^0))] + [e_{sA}(V^0)] \tag{11}
\]

Where \( l_{qA} \) are the stator leakage inductance in phase ‘A’ and \( e_A \) are the back emf in phase ‘A’. Also, (12) is obtained using Figure 9(b).

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sA}(V^1) \\
i_{sB}(V^1)
\end{bmatrix} + \begin{bmatrix}
l_{qA} \* q(i_{qA}(V^1)) \\
l_{qB} \* q(i_{qB}(V^1))
\end{bmatrix} + \begin{bmatrix}
e_{sA}(V^1) \\
e_{sB}(V^1)
\end{bmatrix} \tag{12}
\]

when the dynamic circuit in Figure 9(c) is considered, (13) holds true.

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sB}(V^3) \\
i_{sG}(V^3)
\end{bmatrix} + \begin{bmatrix}
l_{qB} \* q(i_{qB}(V^3)) \\
l_{qG} \* q(i_{qG}(V^3))
\end{bmatrix} + \begin{bmatrix}
e_{sB}(V^3) \\
e_{sG}(V^3)
\end{bmatrix} \tag{13}
\]

Moreover, (14) is obtained using Figure 9(d).

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sG}(V^67) \\
i_{sC}(V^67)
\end{bmatrix} + \begin{bmatrix}
l_{qG} \* q(i_{qG}(V^67)) \\
l_{qC} \* q(i_{qC}(V^67))
\end{bmatrix} + \begin{bmatrix}
e_{sG}(V^67) \\
e_{sC}(V^67)
\end{bmatrix} \tag{14}
\]

When the dynamic circuit in Figure 9(e) is considered, (15) can be derived.

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sC}(V^71) \\
i_{sF}(V^71)
\end{bmatrix} + \begin{bmatrix}
l_{qC} \* q(i_{qC}(V^71)) \\
l_{qF} \* q(i_{qF}(V^71))
\end{bmatrix} + \begin{bmatrix}
e_{sC}(V^71) \\
e_{sF}(V^71)
\end{bmatrix} \tag{15}
\]

Also, when the dynamic circuit in Figure 9(f) is considered, (16) can be derived.

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sF}(V^103) \\
i_{sD}(V^103)
\end{bmatrix} + \begin{bmatrix}
l_{qF} \* q(i_{qF}(V^103)) \\
l_{qD} \* q(i_{qD}(V^103))
\end{bmatrix} + \begin{bmatrix}
e_{sF}(V^103) \\
e_{sD}(V^103)
\end{bmatrix} \tag{16}
\]

Moreover, (17) is obtained using Figure 9(g).

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sD}(V^111) \\
i_{sE}(V^111)
\end{bmatrix} + \begin{bmatrix}
l_{qD} \* q(i_{qD}(V^111)) \\
l_{qE} \* q(i_{qE}(V^111))
\end{bmatrix} + \begin{bmatrix}
e_{sD}(V^111) \\
e_{sE}(V^111)
\end{bmatrix} \tag{17}
\]

Finally, (18) is obtained using Figure 9(h).

\[
\begin{bmatrix}
V_{DC} \\
0
\end{bmatrix} = r_s \* \begin{bmatrix}
i_{sE}(V^127) \\
i_{sF}(V^127)
\end{bmatrix} + \begin{bmatrix}
l_{qE} \* q(i_{qE}(V^127)) \\
l_{qF} \* q(i_{qF}(V^127))
\end{bmatrix} + \begin{bmatrix}
e_{sE}(V^127) \\
e_{sF}(V^127)
\end{bmatrix} \tag{18}
\]

By subtracting every two adjacent equations from each other in addition to neglecting the drop voltage on the \( r_s \) as it will very small quantity and neglecting the back emf as there will be little change on it (19) can be derived.
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The position scalars $P_{sA}$, $P_{sB}$, $P_{sC}$, $P_{sD}$, $P_{sE}$, $P_{sF}$, and $P_{sG}$ can be constructed as given in (20).

\[
\begin{bmatrix}
P_{sA} \\
P_{sB} \\
P_{sC} \\
P_{sD} \\
P_{sE} \\
P_{sF} \\
P_{sG}
\end{bmatrix} = C \times
\begin{bmatrix}
q(i_{sA}(V1) - i_{sA}(V0)) \\
q(i_{sB}(V3) - i_{sB}(V1)) \\
q(i_{sc}(V71) - i_{sc}(V67)) \\
q(i_{sd}(V111) - i_{sd}(V103)) \\
q(i_{se}(V127) - i_{se}(V111)) \\
q(i_{sf}(V103) - i_{sf}(V71)) \\
q(i_{sg}(V67) - i_{sg}(V3))
\end{bmatrix}
\]  

(19)

The position scalars $P_{sA}$, $P_{sB}$, $P_{sC}$, $P_{sD}$, $P_{sE}$, $P_{sF}$, and $P_{sG}$ can be constructed as given in (20).

\[
\begin{bmatrix}
P_{sA} \\
P_{sB} \\
P_{sC} \\
P_{sD} \\
P_{sE} \\
P_{sF} \\
P_{sG}
\end{bmatrix} = C \times
\begin{bmatrix}
q(i_{sA}(V1) - i_{sA}(V0)) \\
q(i_{sB}(V3) - i_{sB}(V1)) \\
q(i_{sc}(V71) - i_{sc}(V67)) \\
q(i_{sd}(V111) - i_{sd}(V103)) \\
q(i_{se}(V127) - i_{se}(V111)) \\
q(i_{sf}(V103) - i_{sf}(V71)) \\
q(i_{sg}(V67) - i_{sg}(V3))
\end{bmatrix}
\]  

(20)

where

\[
C = \frac{V_{DC} - 2L_{fo} + L_{ls}}{L_{x}}
\]  

(21)

To obtain the position signals in all sectors when a failure in the speed sensor is occurred in all sectors, Table 3 can be utilized. These position scalars can be utilized to generate $P_{alpha}$, $P_{beta}$ as (22).

\[
\begin{bmatrix}
P_{alpha} \\
P_{beta}
\end{bmatrix} = [V]
\]  

(22)

where

\[
V = \begin{bmatrix}
1 & \cos 4\theta_x & \cos 8\theta_x & \cos 12\theta_x & \cos 2\theta_x & \cos 6\theta_x & \cos 10\theta_x \\
1 & \sin 4\theta_x & \sin 8\theta_x & \sin 12\theta_x & \sin 2\theta_x & \sin 6\theta_x & \sin 10\theta_x
\end{bmatrix}
\]  

(23)

Figure 8. NSV-SVPWM technique; (a) multi-dimension SVPWM vector synthesis and (b) the PWM waveform for a 7-phase inverter in sector 1

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Moreover, the results demonstrate the algorithm developed in this paper was succeed in extracting the rotor position and speed at low and zero load conditions. Then, the speed command of the speed controller was changed to 0 and the motor operating at full load condition. The results provided by simulating the control structure illustrated in Figure 10 in the SABER simulator are depicted in the Table 3. The stator currents derivatives \( i_a, i_b, i_c, i_d, i_e, \) and \( i_g \) of the motor were measured and the scalar position signals (Palpha, and Pheta) were constructed as (22-23) and Table 3. Then a mechanical observer [29] was utilized to enhance the quality of the estimated position signals by removing the noises. Note the simulation includes a minimum pulse width of 10us when the rate of change of the motors currents was sampled.

The results provided by simulating the control structure illustrated in Figure 10 in the SABER simulator are depicted in the Figure 11. The speed command of the speed controller was set to 180 rpm while the motor operating at full load condition. Then, the speed command of the speed controller was changed to 0 and 180 rpm at times 1.5 s and 3 s respectively. The simulation results demonstrate that the motor measured speed tracked the speed command of the speed controller effectively with good transient and steady-state errors. Moreover, the results demonstrate the algorithm developed in this paper was succeed in extracting the rotor position and speed at low and zero speeds.

![Figure 9. Dynamic equivalent of the 7-phase PMSM during generating different vectors one PWM period](image)

(a) V0 is generated, (b) V1 is generated, (c) V3 is generated, (d) V67 is generated, (e) V71 is generated, (f) V103 is generated, (g) V111 is generated, and (h) V127 is generated.

<table>
<thead>
<tr>
<th>Sector no.</th>
<th>( PS_a=0 )</th>
<th>( PS_b=\alpha )</th>
<th>( PS_c=\beta )</th>
<th>( PS_a=\alpha )</th>
<th>( PS_b=\beta )</th>
<th>( PS_c=0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( i_{aA}^{\alpha} - i_{aA}^{\beta} )</td>
<td>( i_{bB}^{\alpha} - i_{bB}^{\beta} )</td>
<td>( i_{cC}^{\alpha} - i_{cC}^{\beta} )</td>
<td>( i_{dD}^{\alpha} - i_{dD}^{\beta} )</td>
<td>( i_{eE}^{\alpha} - i_{eE}^{\beta} )</td>
<td>( i_{fF}^{\alpha} - i_{fF}^{\beta} )</td>
</tr>
<tr>
<td>2</td>
<td>( i_{aA}^{\alpha} - i_{aA}^{\beta} )</td>
<td>( i_{bB}^{\alpha} - i_{bB}^{\beta} )</td>
<td>( i_{cC}^{\alpha} - i_{cC}^{\beta} )</td>
<td>( i_{dD}^{\alpha} - i_{dD}^{\beta} )</td>
<td>( i_{eE}^{\alpha} - i_{eE}^{\beta} )</td>
<td>( i_{fF}^{\alpha} - i_{fF}^{\beta} )</td>
</tr>
<tr>
<td>3</td>
<td>( i_{aA}^{\alpha} - i_{aA}^{\beta} )</td>
<td>( i_{bB}^{\alpha} - i_{bB}^{\beta} )</td>
<td>( i_{cC}^{\alpha} - i_{cC}^{\beta} )</td>
<td>( i_{dD}^{\alpha} - i_{dD}^{\beta} )</td>
<td>( i_{eE}^{\alpha} - i_{eE}^{\beta} )</td>
<td>( i_{fF}^{\alpha} - i_{fF}^{\beta} )</td>
</tr>
</tbody>
</table>

4. SIMULATION RESULTS

4.1. Saliency position tracking

The proposed algorithm given in Table 3 to get the shaft position and speed of the 7-phase drive when a failure in a speed sensor is occurred is simulated in SABER based on the control scheme shown in Figure 10. The stator currents derivatives \( i_a, i_b, i_c, i_d, i_e, \) and \( i_g \) (of the motor) were measured and the scalar position signals (Palpha, and Pheta) were constructed as (22-23) and Table 3. Then a mechanical observer [29] was utilized to enhance the quality of the estimated position signals by removing the noises. Note the simulation includes a minimum pulse width of 10us when the rate of change of the motors currents was sampled.

The results provided by simulating the control structure illustrated in Figure 10 in the SABER simulator are depicted in the Figure 11. The speed command of the speed controller was set to 180 rpm while the motor operating at full load condition. Then, the speed command of the speed controller was changed to 0 and 180 rpm at times 1.5 s and 3 s respectively. The simulation results demonstrate that the motor measured speed tracked the speed command of the speed controller effectively with good transient and steady-state errors. Moreover, the results demonstrate the algorithm developed in this paper was succeed in extracting the rotor position and speed at low and zero speeds.

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Figure 10. Control structure of the 7-phase drive to estimate the shaft speed and position

Figure 11. Saliency tracking results
4.2. Control of the 7-phase drive in the case of a failure in speed sensor

The schematic of the control structure of the 7-phase drive when a failure in the speed sensor is occurred has been simulated using the SABER simulator. The algorithm developed in this research besides the mechanical observer was used to get the shaft position and the speed of the motor when a failure in the speed sensor is occurred. Then these signals are utilized to achieve sensorless speed-controlled 7-phase PMSM drive as shown in Figure 12.

![Schematic Diagram](image)

Figure 12. Sensorless speed-controlled 7-phase drive

Figure 13 shows the simulation results for a speed-controlled 7-phase motor in the case of a failure in the speed sensor. The speed command of the speed controller was set to 30 rpm and at full load. Then at t=3 s, the speed command of the speed controller was modified to 0 rpm. Finally, at t=5 s the speed command of the speed controller was modified to -30 rpm. The results depicted in Figure 13 demonstrate the excellent dynamic and steady-state response of the whole drive system to the low-speed steps command in the case of a failure in the speed sensor.

Figure 14 shows similar results that were given in Figure 13 but at a higher speed steps command. The speed command of the speed controller of the 7-phase motor drive was set to 300 rpm at full load in the case of a failure in the speed sensor. At t=2 s, the speed command of the speed controller was changed from 300 rpm to 0 rpm. Then at t=3.5 s, the speed command of the speed controller was changed to 300 rpm again. The results demonstrate the excellent response of the whole drive system to the high-speed steps command in the case of a failure in the speed sensor.

Figure 15 illustrates the stability of the 7-phase drive in the case of a failure in the speed sensor when a load disturbance was applied at low speed (100 rpm). The speed command of the speed controller of the 7-phase motor was set to 100 rpm at 20% of the rated load. Then the load on the motor was increased instantly to 80% of the full load at t=1 s. at t=2 s, and the load on the motor was decreased instantly to 20% of the full load. After that, at t=3 s, the speed command of the speed controller was set to 0 rpm. Then it was set to -100 rpm at t=5 s. Finally, the load on the motor was increased instantly to 80% of the full load at t=6 s and decreased instantly to 20% at t=6 s. all these steps in the load and speed were done in the case of a failure in the speed sensor. The results show that the system maintained the speed in all the cases.
Figure 13. Low-speed operation of the 7-phase motor in the case of a failure in the speed sensor

Figure 14. High-speed operation of the 7-phase motor in the case of a failure in the speed sensor
5. CONCLUSION

This paper has presented a new control technique of the 7-phase PMSM drive system in the case of a failure in the speed sensor. This control technique is based on obtaining the rotor position and speed in the case of a failure by tracking the saliency position of the 7-phase PMSM motor using multi-dimension SVPWM techniques. The results have shown the enhanced robustness of the whole drive system at operating conditions.

The implementation of this technique is easy and can be applied to the induction motor also.

REFERENCES


BIOGRAPHIES OF AUTHORS

Kamel Saleh was born in Tulkarm, Palestine, in 1980. He received the B.E. degree in electrical engineering from An-Najah National University in 2003. From 2003 to 2005, he worked as a planning engineer with the Palestinian Energy Authority. In 2005, he joined Nottingham University as a graduate student and obtained a master degree and Ph.D degree in electrical engineering in 2006 and 2009 respectively. From 2009 to 2010, he worked as a researcher with as a power electronics, control, and machine (PEMC) group at Nottingham University. Finally, in 2010 he joined the department of electrical engineering at An-Najah National University as a lecturer. Finally, in 2018 he was promoted to be associated professor. His current researches include sensorless control of multi-phase drive, multilevel inverters drive, DSTATCOM and renewable energy. He can be contacted at email: kamel.saleh@najah.edu.

Mark Sumner received the B.Eng degree in Electrical and Electronic Engineering from Leeds University in 1986 and then worked for Rolls Royce Ltd in Amst, UK. Moving to the University of Nottingham. He completed his Ph.D in induction motor drives in 1990, and after working as a research assistant, was appointed Lecturer in October 1992. He is now Professor of Electrical Energy Systems. His research interests cover control of power electronic systems including sensorless motor drives, diagnostics and prognostics for drive systems, power electronics for enhanced power quality and novel power system fault location strategies. He can be contacted at email: mark.sumner@nottingham.ac.uk.

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