Hybrid Mode Control of an Asymmetric Dual Three-Phase Synchronous Motor under Single-Phase Open Fault

Dong-Kyun Son¹, Dong-Kil Kang¹, Doo-Ill Son¹, Soon-Ho Kwon¹, and Geun-Ho Lee¹

¹Department of Automotive Engineering, Kookmin University, Seoul 02707, South Korea

Corresponding author: Geun-Ho Lee (motor@kookmin.ac.kr).

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ABSTRACT This paper proposes hybrid mode control for an asymmetric dual three-phase synchronous motor (ADTP-SM) with separated neutral points in a single-phase open-fault situation. The fault-tolerant control is classified into the maximum torque mode and minimum loss mode. For an arbitrary phase with an open fault, the combination of phase currents for operation in each mode is derived by mathematical analysis. In maximum torque mode operation, a rotational coordinate transformation is proposed to minimize the performance variance according to the speed. In minimum loss mode operation, a stationary coordinate transformation is proposed to control the harmonics of the phase currents. This stationary coordinate transformation can be applied to arbitrary-phase open-fault situations. In addition, the performances with and without harmonic control are compared and analyzed, and the smoothness of the mode conversion is also analyzed. The validity of the proposed coordinate transformations is verified through experiments at various speeds.

INDEX TERMS Asymmetric dual three-phase synchronous motor (ADTP-SM), fault-tolerant operation, magnetomotive force (MMF), vector space decomposition (VSD).

I. INTRODUCTION

An asymmetric dual three-phase synchronous motor (ADTP-SM) is a two-set motor with three phases per set. This motor offers improved electromagnetic characteristics by adjusting the phase difference between the two sets, with high performance when this phase difference is 30 degrees, so this scenario is being extensively studied. The ADTP-SM has high torque density and low torque ripple characteristics because it has a higher winding number than other motors [1-3].

According to Salem and Narimani, the ADTP-SM has approximately half the phase current of conventional three-phase motors, so the capacity of switching and inverter elements can be reduced [4]. Since the ripple of the DC-link current is low, the size of the DC-link capacitor bank can be reduced. Based on these advantages, this configuration is widely used in motors for electric vehicles (EVs), ships, and aircraft that require high torque density [3], [4]. In addition, by separating the neutral point of each set, reliability can be ensured in a single-phase open-fault situation. Figure 1 shows the topology of the voltage source inverter (VSI) for driving the ADTP-SM, and the neutral points of the two sets are separated [5].

Two methods of coordinate transformation for controlling the ADTP-SM have been studied [4], [6-8]: double-dq methods and vector space decomposition (VSD) methods. The double-dq method implements current control by selecting the dq-axis coordinate system for each set. The VSD method uses the dq-axis for energy conversion and the

*FIGURE 1 Topology of the VSI and ADTP-SM [2,3].*
xy-axis for harmonic current control [9-13]. The current projected on the xy-axis is controlled to be zero.

In the double-dq method, orthogonality is not established because the frequency components projected on each coordinate system are the same. In addition, mutual interference between the two coordinate systems may occur due to mutual inductance between sets, resulting in poor control performance [12], [14-15].

However, when the VSD method is applied, orthogonality is established because different frequency components are projected on the two coordinate systems. Therefore, the control performance is excellent because the dq-axis and the xy-axis can be controlled independently of each other [6-8], [15-16].

According to Estima and Cardoso, single-phase open faults in motors are one of the most common faults along with insulated-gate bipolar transistor (IGBT) faults. The cause of the failure is mainly burnout of the motor winding due to overheating and failure of the VSI circuit [17]. When controlling the ADTP-SM fault tolerance, stable control of the rest of the healthy phase without additional circuits is important. The most basic fault-tolerant control is to open all phases of the fault set and control only the healthy set [18]. This control method is the same as that for the conventional three-phase motor. However, there is a problem in that the mechanical output of the motor is greatly reduced. Therefore, methods to minimize mechanical output reduction by controlling all phases except for the fault phase have been studied [19-24]. When the double-dq method is applied in a post-fault situation, the control performance may be very poor due to the mutual influence between the healthy set and the fault set [15], [25]. Therefore, in the present paper, the VSD method is applied for fault-tolerant control. The ADTP-SM fault-tolerant control includes a maximum torque (MT) mode and a minimum loss (ML) mode.

The MT mode is a control method that generates the MT under the same current limit condition to generate the same magnetomotive force (MMF) as in the healthy state [19], [26-28]. The ML mode is a method to minimize copper loss during operation. This method constrains the current that does not contribute to the mechanical output to zero [28,29].

In previous studies using VSD, AC current commands were input into the xy-axis stationary coordinate system to operate in the MT mode [25-30]. As the speed increases, the frequency of the AC current command also increases, so the control performance is degraded. This paper proposes a rotational coordinate transformation of the xy-axis for MT mode operation. In this way, a DC current command can be input into the xy-axis system so that the variance in the control performance due to speed changes can be reduced.

When operating in the ML mode, the components projected on the xy-axis vary depending on the phase in which the open fault occurs. When VSD is applied, if the open fault occurs in the c2-phase, then the fundamental wave of the current is not projected on the x-axis, and only the harmonic current is projected. Therefore, the projected harmonic current can be effectively controlled by constraining the x-axis value to zero. However, when the open fault occurs in the b1-phase, effectively controlling the harmonic current is difficult because the fundamental wave of the current is projected on both the x-axis and the y-axis. Therefore, this paper proposes a new xy-axis coordinate transformation for ML mode operation. This changes only the coordinate transformation of the x-axis regardless of the phase in which the open fault occurs so that the fundamental current is not projected and only the harmonic current is projected.

In Section II, we mathematically derive the combinations of the phase currents for operation in the MT mode and ML mode. Section III introduces the new coordinate transformations of the xy-axis for the MT mode and ML mode. Section IV conducts comparative verification with existing studies through experiments, and Section V provides the conclusion.

II. CURRENT COMBINATION FOR MT AND ML MODE OPERATION

In this section, the combinations of the phase currents for operating in the MT mode and ML mode are derived using mathematical equations. The assumptions for the formulas include ignoring the saturation phenomenon of the inductance, harmonics of the voltage and current, and nonlinearity of the VSI. This paper describes the situation in which a single-phase open fault occurs in the c2-phase for formula development.

A. Current combinations for the MT mode

The MT mode generates MMFs of the same amplitude as that in the healthy state, and the healthy set and fault set generate MMFs of the same amplitude. (1) is the MMF in the healthy state, and the amplitudes of the currents in each phase are the same. The amplitudes of the MMFs created by the two sets are 3NIo, where N is the number of turns in series per phase, and Io is the magnitude of each dq-axis current vector [20]. For convenience, 3NIo is expressed as 1.0 p.u. (2) is each phase current, where \( \omega \) is the rotation angular velocity, \( t \) is the time, and \( \phi \) is the phase difference of the phase currents. Each set generates an MMF of the same

\[
MMF = N \left[ \cos \left( \theta - \frac{0\pi}{6} \right) \times i_{i1} + \cos \left( \theta - \frac{4\pi}{6} \right) \times i_{i2} + \cos \left( \theta + \frac{8\pi}{6} \right) \times i_{i3} \right]
\]

\[
\begin{align*}
i_{i1} &= A_1 \cos \left( \omega t - \phi_1 \right) \\
i_{i2} &= B_1 \cos \left( \omega t - \phi_2 \right) \\
i_{i3} &= C_1 \cos \left( \omega t - \phi_3 \right) \\
i_{o1} &= A_2 \cos \left( \omega t - \phi_4 \right) \\
i_{o2} &= B_2 \cos \left( \omega t - \phi_5 \right) \\
i_{o3} &= C_2 \cos \left( \omega t - \phi_6 \right)
\end{align*}
\]
amplitude, and the sum of the MMFs of each set is 1.0 p.u. Therefore, the healthy set and fault set generate 0.5 p.u. Since the neutral points of each set are separated, the currents in phases \(a_2\) and \(b_2\) are zero. \(a_2\) according to Kirchhoff’s current law.

(4) is the MMF generated in the fault set, and (5) is the current to generate an MMF of 0.5 p.u. (6) is the MMF of the healthy set developed using trigonometric functions, and the sum of the MMFs of (5) and (6) is 1.0 p.u. The amplitudes of the DC component and cosine term in (6) are \(3I_m\), and the amplitude of the sine term is zero. Since the number of variables is greater than the number of equations, obtaining a complete solution difficult.

\[
\begin{align*}
\frac{i_{a_2}}{I_m} &= A_2 \cos(\omega t - \phi_2) \\
\frac{i_{b_2}}{I_m} &= -A_2 \cos(\omega t - \phi_4) \\
\frac{i_{c_2}}{I_m} &= 0
\end{align*}
\]

\[
MMF_{\text{Healthy}} = \frac{3NA_2}{2}\left\{\cos(2\theta - \phi_2) + \cos(-\phi_1)\right\}
\]

\[
\begin{align*}
\frac{i_{a_2}}{I_m} &= \sqrt{3}I_m \cos(\omega t) \\
\frac{i_{b_2}}{I_m} &= -\sqrt{3}I_m \cos(\omega t + \pi) \\
\frac{i_{c_2}}{I_m} &= 0
\end{align*}
\]  

Referring to the paper of Jen-Ren Fu and Lipo, we assume that the amplitude of the current is \(\sqrt{3}I_m\) for the balanced MMF [20]. For the current at which the cosine term in (5) is eliminated, the healthy set generates an MMF of 0.5 p.u., as shown in (7). As a result, to generate a balanced MMF in the MT mode, the current in one phase of the healthy set should be 0. For additional formula expansion of the MT mode, please refer to the appendix.

Figure 2 shows the spatial MMF distribution of the healthy and fault sets when operating in the MT mode. The red line is the MMF occurring in the healthy set, and the blue line is the MMF occurring in the fault set. In addition, the black line is the MMF in the MT mode. The amplitudes of the MMFs in each set are the same, and the sum of the MMFs has the same amplitude as the MMF in the healthy state.

Table 1 shows the phase shifts of the currents in MT mode operation for arbitrary-phase open faults. The amplitude of the currents for the \(x\) terms is zero, and that for the remaining terms is \(\sqrt{3}I_m\).

### Table I
PHASE SHIFTS OF CURRENT COMBINATIONS IN MT MODE OPERATION

| MT mode | \(\phi_1\) | \(\phi_2\) | \(\phi_3\) | \(\phi_4\) | \(\phi_5\) |
|---------|-----------|-----------|-----------|-----------|-----------|
| a1      | \(\times\) | -\(\pi/2\) | \(\pi/2\) | 0         | \(-\pi\)  |
| b1      | \(-\pi/6\) | \(\times\) | 5\(\pi/6\) | \(\times\) | -2\(\pi/3\)| \(\pi/3\) |
| c1      | \(\pi/6\)  | -5\(\pi/6\) | \(\times\) | -\(\pi/3\) | \(\times\) | 2\(\pi/3\) |
| a2      | \(-\pi/6\) | \(\times\) | 5\(\pi/6\) | \(\times\) | -2\(\pi/3\) | \(\pi/3\) |
| b2      | \(\pi/6\)  | -5\(\pi/6\) | \(\times\) | -\(\pi/3\) | \(\times\) | 2\(\pi/3\) |
| c2      | \(\times\) | -\(\pi/2\) | \(\pi/2\) | 0         | -\(\pi\)  | \(\times\) |

### B. Current combinations for the ML mode
The purpose of the ML mode is to maintain the mechanical output of the ADTP-SM and minimize the copper loss. This means that the current that does not contribute to the mechanical output must be controlled to be zero. The copper loss occurring in the ADTP-SM can be expressed as (8), where \(R_a\) is the armature resistance. To derive the current combinations in the ML mode, coordinate transformation is performed on the current on the \(dq\)-axis that contributes to the mechanical output.

(9) is a \(dq\)-axis coordinate transformation using VSD in the healthy state. (10) and (11) are the rotational and stationary coordinate transformations, respectively, of the \(dq\)-axis, where \(f\) is an arbitrary variable of the ADTP-SM, and the “s” and “r” superscripts indicate the stationary coordinate system and the rotational coordinate system, respectively.

(12) is the phase current combination for operation in the ML mode derived using (9), and the maximum current of each phase is \(\sqrt{3}/2I_m\). Figure 3 shows the spatial MMF distribution of the healthy and fault sets when operating in the ML mode. Although the amplitudes of the MMFs generated in each set are different, the sum of the MMFs has the same amplitude as the MMF in the healthy state.
The copper losses can be defined as the average copper loss is defined as the average copper losses occurring in all phases. Table IV shows the DF values and average copper losses for each situation.

\[
J_{Copper} = R_a \left( i_{a1}^2 + i_{b1}^2 + i_{c1}^2 + i_{a2}^2 + i_{b2}^2 + i_{c2}^2 \right)
\] (8)

\[
\begin{bmatrix}
  f_d^e \\
  f_q^e
\end{bmatrix}^T = T_{dq-VSD}^{-1} T_{dq-VSD} = \begin{bmatrix}
  f_d \\
  f_q
\end{bmatrix}
\] (9)

\[
T_{dq-VSD} = \begin{bmatrix}
  \cos(\theta) & \sin(\theta) \\
  -\sin(\theta) & \cos(\theta)
\end{bmatrix}
\] (10)

\[
T_{dq-VSD} = \begin{bmatrix}
  \cos\left(\frac{1}{6}\phi_1\right) & \cos\left(-\frac{4}{6}\phi_1\right) & \cos\left(-\frac{8}{6}\phi_1\right) & \cos\left(-\frac{1}{6}\phi_1\right) & \cos\left(-\frac{5}{6}\phi_1\right) & \cos\left(-\frac{9}{6}\phi_1\right) \\
  -\sin\left(\frac{1}{6}\phi_1\right) & -\sin\left(-\frac{4}{6}\phi_1\right) & -\sin\left(-\frac{8}{6}\phi_1\right) & -\sin\left(-\frac{1}{6}\phi_1\right) & -\sin\left(-\frac{5}{6}\phi_1\right) & -\sin\left(-\frac{9}{6}\phi_1\right)
\end{bmatrix}
\] (11)

\[
i_{a1} = I_a \cos \theta
\]

\[
i_{b1} = \frac{\sqrt{3}}{2} I_a \cos\left(\theta - 0.589\pi\right)
\]

\[
i_{c1} = \frac{\sqrt{3}}{2} I_a \cos\left(\theta + 0.589\pi\right)
\]

\[
i_{a2} = \frac{\sqrt{3}}{2} I_a \cos \theta
\]

\[
i_{b2} = \frac{\sqrt{3}}{2} I_a \cos\left(\theta - \pi\right)
\]

\[
i_{c2} = \frac{\sqrt{3}}{2} I_a \cos\left(\theta - 0.589\pi\right)
\] (12)

Tables II and III show the amplitudes and phase shifts, respectively, of the currents in ML mode operation when an arbitrary-phase open fault occurs. In the post-fault scenario, both the MT mode and the ML mode reduce the operating range that can be output compared to the healthy state.

Therefore, the performance degradation is defined using the derating factor (DF). (13) is the definition of the DF, defined as the ratio of the peak current in the fault state to the peak current in the healthy state under the same output conditions, where \(I_{phase}\) refers to all phase currents. In addition, the average copper loss can be defined as the phase current for each mode. The average copper loss is defined as the average of the copper losses occurring in all phases. Table IV shows the DF values and average copper losses for each situation.

\[
DF = \max\left(\frac{\left|I_{phase}\right|_{healthy}}{\left|I_{phase}\right|_{post\ fault}}\right)
\] (13)

III. COORDINATE TRANSFORMATION FOR MT AND ML MODE OPERATION

In this section, the coordinate transformations for operating in the MT mode and ML mode are described.

A. Coordinate transformation for the MT mode

VSD coordinate transformation is used to operate in the MT mode. (14) is the xy-axis stationary coordinate transformation using VSD, and (15) is the \(dq\)-axis and \(x'y'\)-axis currents when the stationary coordinate transformation is applied [6-8]. (16) is the result of applying the current combination for MT mode operation to (15). The \(dq\)-axis and \(x'y'\)-axis current vectors have the same amplitudes and a phase shift of \(\pi\). As seen from (15), the amplitudes of the \(q\)-axis current and the \(y'\)-axis current are the same. Additionally, since the amplitudes of the \(dq\)-axis current vector and the \(x'y'\)-axis

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**TABLE II**

| ML mode | Amplitude | \(A_1\) | \(B_1\) | \(A_2\) | \(B_2\) | \(C_2\) |
|---------|-----------|-------|-------|-------|-------|-------|
| Fault phase | \(a_1\) \(\times\) \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | 1 |
| | \(b_1\) \(\sqrt{3}/2\) \(\times\) | \(\sqrt{3}/2\) | 1 | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | 1 |
| | \(c_1\) \(\sqrt{3}/2\) \(\times\) | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | 1 | \(\sqrt{3}/2\) | 1 |
| | \(a_2\) 1 | \(\sqrt{3}/2\) \(\times\) | \(\sqrt{3}/2\) | 1 | \(\sqrt{3}/2\) | 1 |
| | \(c_2\) 1 | \(\sqrt{3}/2\) \(\times\) | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | \(\sqrt{3}/2\) | \(\times\) |

**TABLE III**

| ML mode | Phase shift | \(\phi_1\) | \(\phi_2\) | \(\phi_3\) | \(\phi_4\) | \(\phi_5\) | \(\phi_6\) |
|---------|-------------|-------|-------|-------|-------|-------|-------|
| Fault phase | \(a_1\) \(\times\) | \(-\pi/2\) | \(-2\pi/3\) | 0.089\(\pi\) | -3\(\pi/2\) | 0.911\(\pi\) | |
| | \(b_1\) \(-\pi/6\) \(\times\) | 5\(\pi/6\) | \(-\pi/6\) | 0.75\(\pi\) | 1.57\(\pi\) | |
| | \(c_1\) \(\pi/6\) \(\times\) | \(-5\pi/6\) | \(-2\pi/3\) | 0.244\(\pi\) | -5\(\pi/6\) | 1.42\(\pi\) | |
| | \(a_2\) 0.078\(\pi\) \(\times\) | \(-2\pi/3\) | 1.25\(\pi\) | \(2\pi/3\) | 3\(\pi/2\) | |
| | \(b_2\) \(-1.922\) \(\times\) | 0.744\(\pi\) | 2\(\pi/3\) | 0.316\(\pi\) | \(2\pi/3\) | |
| | \(c_2\) 0 | 0.589\(\pi\) | 0.589\(\pi\) | 0 | \(-\pi\) | \(\times\) |

**FIGURE 3** Spatial MMF distribution in the ML mode
applying the method of the reference paper, and the superscript “<sup>e</sup>” of each variable indicates the command value [16]. Using Table V, (14) and (17), we change the xy-axis coordinate transformation according to the fault situation.

\[
T_{xy, \text{MT}} = \begin{bmatrix}
\cos\frac{\theta}{6} & \cos\frac{\pi}{6} & \cos\frac{\theta}{6} \\
\sin\frac{\theta}{6} & -\sin\frac{\pi}{6} & -\sin\frac{\theta}{6}
\end{bmatrix}
\]  

(14)

\[
i_x = \frac{1}{3}(i_{aux} - \frac{1}{2}i_{ay} - \frac{1}{2}i_{ay} + \sqrt{3}i_{az})
\]

\[
i_y = \frac{1}{3}(\sqrt{3}i_{ax} - \sqrt{3}i_{ay} - i_{az})
\]

\[
i_z = \frac{1}{3}(i_{aux} - \frac{1}{2}i_{ay} - \frac{1}{2}i_{ay} - \sqrt{3}i_{az})
\]

\[
i_\theta = \frac{1}{3}(\frac{\sqrt{3}}{2}i_{ax} + \frac{\sqrt{3}}{2}i_{ay} + i_{az}) = i_x
\]

(15)

\[
i_x = \frac{I_a}{3} \left[ \cos \left( \frac{\theta - \frac{\pi}{2}}{2} \right) + \cos \left( \frac{\theta + \frac{\pi}{2}}{2} \right) + 3 \cos \theta \right] = I_a \cos \theta
\]

\[
i_y = \frac{I_a}{3} \left[ \frac{3}{2} \left( \cos \left( \frac{\theta - \frac{\pi}{2}}{2} \right) - \cos \left( \frac{\theta + \frac{\pi}{2}}{2} \right) \right) \right] = I_a \sin \theta
\]

\[
i_z = \frac{I_a}{3} \left[ \frac{3}{2} \left( \cos \left( \frac{\theta - \frac{\pi}{2}}{2} \right) + \cos \left( \frac{\theta + \frac{\pi}{2}}{2} \right) - 3 \cos \theta \right) \right] = I_a \cos(\theta + \pi)
\]

\[
i_\theta = \frac{I_a}{3} \left[ \frac{3}{2} \left( \cos \left( \frac{\theta - \frac{\pi}{2}}{2} \right) - \cos \left( \frac{\theta + \frac{\pi}{2}}{2} \right) \right) \right] = I_a \sin(\theta + \pi)
\]

(16)

\[
T_{xy, \text{MT}} = \begin{bmatrix}
\cos(\theta + \theta_{MT}) & \sin(\theta + \theta_{MT}) \\
-\sin(\theta + \theta_{MT}) & \cos(\theta + \theta_{MT})
\end{bmatrix}
\]  

(17)

current vector are the same, the amplitudes of the dq-axis current and the x'y-axis current must also be the same. In many papers, the current command value for the x'y-axis is inputted as (16) [23], [25-30]. Since the command is an AC value, it is affected by the electrical angular frequency, and as the speed increases, the control performance decreases.

This paper proposes a new rotational coordinate transformation to maintain the control performance in the MT mode. This approach can maintain the control performance by inputting a DC current command value through rotational coordinate transformation of the x'y-axis current. To derive the phase shifts for the dq'-axis and the x'y-axis in the case of an arbitrary-phase open fault, the phase current combinations in Table I are applied to (9). When applied to all the phases in the same way as in (16), the phase shifts can be derived.

Table V shows the phase shifts for the dq'-axis and the x'y-axis of the stationary coordinate system in the case of an arbitrary-phase open fault. By using these phase shifts, the dq'-axis and the x'y-axis can be synchronized. (17) is the x'y-axis rotational coordinate transformation for MT mode operation.

Figure 4 shows a current control block diagram for operating in the MT mode. The output voltage of the current controller is converted into a stationary coordinate system voltage through coordinate transformation. Then, space vector pulse width modulation (SVPWM) is applied to input the PWM signal to each phase switch. The SVPWM step

B. Coordinate transformation for the ML mode

To operate in the ML mode, the current that does not contribute to the mechanical output must be zero. However, as seen from (15), the q'-axis current and the y'-axis current have the same amplitude and different signs. These components contribute to the mechanical output since the y'-axis current becomes the same as the dq'-axis current when the open fault occurs in the c2-phase. If harmonics are not included in the phase current, then the component projected on the x'-axis is zero, as in (18).

\[
i_x = \frac{I_a}{3} \left[ \cos \theta - \frac{\sqrt{3}}{4} \cos(\theta - 0.589\pi) - \frac{\sqrt{3}}{4} \cos(\theta + 0.589\pi) \right] = 0
\]  

(18)

\[
i_s = \frac{1}{3} \left[ \frac{3}{2} i_{ax} - \frac{\sqrt{3}}{2} i_{ay} + \frac{\sqrt{3}}{2} i_{az} \right]
\]

\[
i_s = \frac{1}{3} \left[ \frac{3}{2} i_{ax} + \frac{1}{2} i_{ay} + \frac{1}{2} i_{az} - i_{az} \right]
\]  

(19)
contribute to the mechanical output and causes an additional loss, so the current on the $x^i$-axis is controlled to be zero to minimize the copper loss. The component projected on the $x'y'$-axis varies depending on the phase in which the open fault occurs. When the open fault occurs in the $b_1$-phase, if the stationary coordinate transformation of (14) is applied, then the current projected on the $x'y'$-axis is (19). Unlike the $c_2$-phase open-fault situation, the fundamental wave component of the phase current is projected on the $x'y'$-axis, so both axes must be controlled. However, by changing the phase shift for the $x'$-axis according to the open-fault situation, ML mode operation is possible without additional control of the $y'$-axis.

This paper proposes a method of changing the phase shift for the $x'$-axis so that the fundamental wave current projected on the $x'$-axis becomes zero. This makes the motor independently controllable, as only harmonic currents are projected onto the $x'$-axis. Figures 5 (a) and (b) show the coordinate axes selected for ML mode operation when open faults occur in phases $c_2$ and $b_1$, respectively.

(20) is the stationary coordinate transformation of the $x'$-axis in the case of an arbitrary open fault, and (21) is the result of applying the current combination for ML mode operation to (20) when the open fault occurs in the $b_1$-phase. The projected fundamental wave component on the $x'$-axis becomes zero. Therefore, when an open fault occurs in an arbitrary phase, only the harmonic current projected on the $x'$-axis needs to be controlled by applying the coordinate transformation of (20).

During ML mode operation, the current command value for the $x'$-axis is always zero, which is a DC value. Therefore, there is no performance variance according to the rotation speed, so additional rotational coordinate transformation is not required. Figure 6 shows the current control block diagram for ML mode operation. Using Table VI and (20), we adjust the $x'y'$-axis coordinate transformation according to the fault situation.

IV. EXPERIMENTAL VALIDATION

The experimental environment is shown in Figure 7; a two-level VSI is used for the input power of the ADTP-SM. The digital signal processor (DSP) uses an MPC5744P from NXP Semiconductors. It is controlled using 12 PWM signals, and

![FIGURE 5 Vector diagram in the case of a single-phase open fault: (a) c2-phase open fault and (b) b1-phase open fault](image)

![FIGURE 6 Block diagram for ML mode operation](image)

![TABLE VI PHASE SHIFTS OF CURRENT COMBINATIONS FOR ML MODE OPERATION](image)

![FIGURE 7 Picture of the experimental setup.](image)
the switching frequency is 16 kHz. The ADTP-SM is a claw-pole-type ADTP-SM, and the two sets of neutral points are separated. The parameters of the ADTP-SM are as follows: the number of poles is 16, the average value of the field-linkage flux is 14.3 mWb, \( R_e \) is 12.57 m\( \Omega \), and the average value of the self-inductance is 0.05 mH. We apply a DC-link voltage of 48 V. Two 4-channel oscilloscopes are used to measure phase currents.

When acquiring torque data, the average torque can be analyzed, but the torque ripple can be affected by the dynamometer. Therefore, the control algorithm only compares the amplitude of the torque ripple. For the experiment, the dynamometer controls the speed, and the ADTP-SM controls the current. The torque command value is 7.7 Nm, and the corresponding armature current applies a \( d \)-axis current of -50 A, a \( q \)-axis current of 34.2 A, and a field current of 3 A. To analyze the performance variance according to the speed, the experiment is conducted at 500 rpm, 1000 rpm and 1500 rpm.

There are several methods for detecting an ADTP-SM fault. In this paper, fault occurrence is detected using oscillation of the \( d-q \)-axis current feedback during faults. Additionally, since the two sets of neutral points are separated, the fault phase was detected using Kirchhoff’s current law [31–36].

When an open fault occurs, the torque generated by the fault set rapidly decreases. Additionally, the control can be unstable due to mutual interference between the two sets.

![FIGURE 8 Current waveform controlled using proposed MT at 500 rpm: (a) \( d-q \)-axis current command and feedback current waveform, (b) \( x-y \)-axis current command and feedback current waveform, (c) trajectories of the stationary coordinate system current, (d) current waveforms of the healthy set, and (e) current waveforms of the fault set.](image)

![FIGURE 9 Current waveform controlled using conventional MT at 500 rpm: (a) \( d-q \)-axis current command and feedback current waveform, (b) \( x \)-axis current command and feedback current waveform, (c) trajectories of the stationary coordinate system current, (d) current waveforms of the healthy set, and (e) current waveforms of the fault set.](image)
Therefore, fast fault detection is required. In the experiments in this paper, the MT and ML mode are immediately switched to when an open fault occurs, and the steady-state characteristics obtained with the proposed method and with the conventional method are compared [15, 27].

In the MT mode, the control performances when an AC current command is inputted into the stationary coordinate system and when a DC current command is inputted by applying the proposed coordinate transformation are compared. For convenience, the former is referred to as conventional MT, and the latter is referred to as proposed MT. In the ML mode, the control performances when the harmonics are controlled and when they are not controlled are compared. For convenience, the former is referred to as controlled ML, and the latter is referred to as noncontrolled ML. In addition, when an open fault occurs in the \( b_1 \)-phase, the currents projected on the \( x^s \)-axis when performing the conventional coordinate transformation of (14) and the proposed coordinate transformation of (20) are compared.

### A. MT mode experiment

Figures 8 and 9 show the results of the proposed MT mode and conventional MT mode, respectively. As shown in Figure 8 (a) and Figure 9 (a), the current control characteristics for the \( d^s q^s \)-axis are almost the same. The \( x^s y^s \)-axis current in Figure 8 (b) is stably controlled.

On the other hand, a delay occurs between the \( x^s \)-axis current feedback and AC current command in Figure 9 (b). Since this is an error, the control performance is low. Figures 8 (c) and 9 (c) show the trajectories of the stationary coordinate system current. When the proposed MT mode is applied, the trajectories for the \( d^s q^s \) and \( x^s y^s \) axes are circular. However, when the conventional MT mode is applied to the \( x^s \)-axis, the trajectory for the \( x^s y^s \)-axis is elliptical due to the low control performance.

Figures 8 (d), (e) and 9 (d), (e) show the waveforms of each phase current. To operate in the MT mode, the amplitude of the \( a_1 \)-phase current is zero.

Figure 10 shows the fast Fourier transform (FFT) analysis of the \( a_1 \)-phase current during the \( c_2 \)-phase open fault. When performing FFT analysis, waveforms with multiple periods were analyzed to reduce measurement errors. The first harmonic order is the rotation angular frequency. The fundamental wave amplitude of the \( a_1 \)-phase current is approximately 8.4 A for conventional MT and approximately 0.7 A for proposed MT. When the proposed method is applied, the fundamental wave component of the \( a_1 \)-phase current can be lowered. From this result, in the case of conventional MT, additional loss and torque ripple may occur due to the \( a_1 \)-phase current.

Figure 11 shows the torque profiles when conventional MT and proposed MT are applied. Both methods result in the same average torque of 7.7 Nm, but the torque ripple is approximately 46.1% higher when conventional MT is applied.

Figure 12 shows the copper loss profiles in the ADTP-SM when conventional MT and proposed MT are applied. The average copper loss is 5.7% higher when conventional MT is applied: 20.9 W for proposed MT and 22.1 W for conventional MT.
B. ML mode experiment

Figure 15 shows the results of controlled ML, and Figure 16 shows the results of noncontrolled ML. As seen from Figures 15 (a) and 16 (a), the current control characteristics for the $d'q'$-axis are almost the same. The $x'$-axis current in Figure 15 (b) is stably controlled to be zero, whereas the $x'$-axis current in Figure 16 (b) is not controlled to be zero and fluctuates to a large extent. This fluctuation represents the harmonic current projected on the $x'$-axis, as mentioned in the ML mode discussion of Section III. Figures 15 (c) and 16 (c) show the trajectories of the stationary coordinate system current; the $d'q'$-axis current trajectories are both circular. As shown in (15), the amplitude of the $y'$-axis current is the same as that of the $q'$-axis current, and the $x'$-axis current must be zero; thus, the $x'y'$-axis current trajectory must be straight. In contrast to Figure 15 (c), the $x'y'$-axis current trajectory in Figure 16 (c) is a distorted straight line. This represents unsatisfactory operation in the ML mode and may cause additional loss.

Figures 15 (d), (e), and 16 (d), (e) show the waveforms of
each phase current. When the current on the $x^*$-axis is controlled to be zero, the waveforms of the healthy phase current are more sinusoidal. Figure 17 shows the FFT analysis of the $a_1$-phase current during the $c_2$-phase open fault. The total harmonic distortion (THD) of the $a_1$-phase current is 6.12% for controlled ML and 11.08% for noncontrolled ML. Figure 18 shows the torque profiles. The average torque is the same at 7.7 Nm for both methods, and the torque ripple is approximately 4.44% higher when noncontrolled ML is applied compared to controlled ML.

Figure 19 shows the copper loss occurring in the ADTP-SM when noncontrolled ML and controlled ML are applied. The average copper loss is 2.1% higher when noncontrolled ML is applied: 16.28 W for controlled ML and 16.62 W for noncontrolled ML.

This difference is caused by the $x^*$-axis current and can be

![Image](image_url)

**FIGURE 15** Current waveform controlled using controlled ML at 500 rpm: (a) $d^*q^*$-axis current command and feedback current waveform, (b) $x^*y^*$-axis current command and feedback current waveform, (c) trajectories of the stationary coordinate system current, (d) current waveforms of the healthy set, and (e) current waveforms of the fault set.

![Image](image_url)

**FIGURE 16** Current waveform controlled using noncontrolled ML at 500 rpm: (a) $d^*q^*$-axis current command and feedback current waveform, (b) $x^*y^*$-axis current command and feedback current waveform, (c) trajectories of the stationary coordinate system current, (d) current waveforms of the healthy set, and (e) current waveforms of the fault set.
compared to controlled ML, the $x'y'$-axis current trajectory becomes more distorted as the speed increases. This means that as the speed increases, the fluctuation of the $x'$-axis current increases.

On the other hand, in the case of controlled ML, there is almost no distortion because the controller controls the $x'$-axis current to be zero. As a result, when operating in the ML mode, controlling the $x'$-axis current to be zero using (20) shows higher control performance. Figure 22 shows the $d'q'$-axis current, $x'$-axis current, and phase current waveforms when an open fault occurs in the $b1$-phase. Figure 22 (a) shows the result of applying the conventional VSD coordinate conversion of (14), and the fundamental wave is projected on the $x'$-axis. In contrast, Figure 22 (b) shows the result of applying the coordinate transformation proposed in (20), and only harmonics are projected on the $x'$-axis.

Figures 22 (c), (d) and (e) show the results of controlling the harmonics projected on the $x'$-axis to be zero; control can be achieved in the same way as in Figure 15, where an open changed according to the rotation speed. Figures 20 and 21 show the phase current waveforms and the stationary coordinate system current trajectories during noncontrolled ML and controlled ML operation at 1000 rpm and 1500 rpm, respectively. In the case of noncontrolled ML.
fault occurs in the $c_2$-phase.

If the proposed coordinate transformation is applied, then the ML mode can be driven by controlling only the $x^a$-axis to be zero regardless of the open-fault phase. Figure 23 shows the results of mode conversion during current control using the method proposed in (17) and (20). Therefore, when controlling the fault tolerance, control can be achieved by appropriate mode conversion considering the $DF$.

![Figure 21](image_url)  
**FIGURE 21** Comparison of current waveforms according to coordinate transformation when operating in the ML mode at 1500 rpm. (a), (b), and (c) show the results of controlled ML; (d), (e) and (f) show the results of noncontrolled ML.

![Figure 22](image_url)  
**FIGURE 22** Comparison of the current projected on the $x^c$-axis according to coordinate transformation when operating in the ML mode at 500 rpm: (a) $x^c$-axis current using the conventional stationary coordinate transformation of (14) and $dq^c$-axis currents and (b) $x^c$-axis current using the proposed stationary coordinate transformation of (20) and $dq^c$-axis currents; (c), (d), and (e) are current waveforms in which the $x^a$-axis value is controlled to be zero using the proposed coordinate transformation of (20).
V. CONCLUSIONS
This paper analyzes the single-phase open-fault situation for an ADTP-SM in which two sets of neutral points are separated. In the case of fault-tolerant control, the motor can be operated in the MT mode or ML mode. Through mathematical analysis, the combinations of phase currents in MT mode and ML mode operation are derived for all phases. The effect on the control performance when the current command for the \( x^1 \)-axis is an AC value in MT mode operation is explained. This brings a disadvantage in that the control performance is lowered because the frequency of the current command must increase as the speed increases. If the proposed rotational coordinate transformation (17) is used, then the performance can be improved because the motor can be controlled by a DC current command value.

During ML mode operation, the component projected on the \( x^2y^1 \)-axis varies depending on the fault phase, and the fundamental wave component can be projected depending on the fault phase; thus, the motor is difficult to control. If the proposed coordinate transformation (20) is used, then only harmonics are projected on the \( x^2 \)-axis, so the motor can be independently controlled. The control characteristics of the proposed algorithm at various speeds are analyzed, and the generated torque and copper loss are compared. Additionally, the performance difference according to the \( x^2 \)-axis control in the ML mode is analyzed. Both the MT and ML modes improve the control characteristics under the control using the proposed algorithm. In addition, smooth mode conversion is possible, so the motor can be controlled in an appropriate mode according to the load characteristics.

APPENDIX
Equation expansion for the current combinations in MT mode operation. Current combination when the open fault occurs in the \( c_2 \)-phase. The paper by Jen-Ren Fu and Lipo was referred to. The MMFs of each of the two sets are the same, and the sum of the two MMFs is equal to the MMF in the healthy state.

(22) is the MMF generated by the fault set, and \( \phi_1 \) must be zero to attain the maximum value. Additionally, the MMFs

\[
\text{MMF}_{\text{fault}} = \frac{1}{\sqrt{3}} L A \cos \left( \theta - \frac{\pi}{6} \right) \times A_c \cos \left( \theta - \phi_1 \right) + \cos \left( \theta - \frac{5\pi}{6} \right) \times \left\{ -A_c \cos \left( \theta - \phi_1 \right) \right\}
\]

\[
= \sqrt{3} N A \left( \cos \left( 2\theta - \phi_1 \right) + \cos \left( -\phi_1 \right) \right)
\]

(22)

\[
\text{MMF}_{\text{motor}} = \frac{N}{2} \times \left[ \cos \left( 2\theta \right) \times \left\{ A_c \cos \phi_1 + B_c \cos \left( \phi_2 - \frac{2\pi}{3} \right) + C_c \cos \left( \phi_1 + \frac{2\pi}{3} \right) \right\} + \right.
\sin \left( 2\theta \right) \times \left\{ A_c \sin \phi_1 + B_c \sin \left( \phi_2 + \frac{2\pi}{3} \right) + C_c \sin \left( \phi_1 - \frac{2\pi}{3} \right) \right\} \right]
\]

(23)

\[
3 I_m = A_c \cos \phi_1 + B_c \cos \left( \phi_2 - \frac{2\pi}{3} \right) + C_c \cos \left( \phi_1 + \frac{2\pi}{3} \right)
\]

\[
= A_1 \cos \phi_1 + B_1 \cos \left( \phi_2 + \frac{2\pi}{3} \right) + C_1 \cos \left( \phi_1 - \frac{2\pi}{3} \right)
\]

\[
B_1 \left\{ \cos \left( \phi_1 - \frac{2\pi}{3} \right) - \cos \left( \phi_1 + \frac{2\pi}{3} \right) \right\} + C_1 \left\{ \cos \left( \phi_1 + \frac{2\pi}{3} \right) - \cos \left( \phi_1 - \frac{2\pi}{3} \right) \right\} = 0
\]

\[
B_1 \left\{ \sin \phi_1 \sin \left( \frac{2\pi}{3} \right) \right\} - C_1 \left\{ \sin \phi_1 \sin \left( \frac{2\pi}{3} \right) \right\} = 0
\]

\[
A_1 \sin \phi_1 + B_1 \sin \left( \phi_2 + \frac{2\pi}{3} \right) + C_1 \sin \left( \phi_1 - \frac{2\pi}{3} \right) = 0
\]

of the healthy set and fault set should be 1.5\( N_m \), and the value of \( A_2 \) is \( \sqrt{3} I_m \).

(23) is the MMF generated by the healthy set. (24) to (27) are modified expansions of (23). The sizes of the first term in (23) and the cosine term are the same, and the sum of the MMFs of the two sets becomes 3\( N_m \) only when the sine term becomes zero. To satisfy the balanced MMF, \( B_1 \) and \( C_1 \) become \( \sqrt{3} I_m \), and the phases become \( \phi_2 = \pi/2 \) and \( \phi_3 = -\pi/2 \).

(27) is the sine term of (23), and to make it 0, the value of \( A_1 \) must be zero. As a result, the sum of the MMFs of the two sets is 3\( N_m \).

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**Dong-Kyun Son** received a bachelor’s degree in electrical engineering from Ulsan University, Ulsan, South Korea, in 2017. He is currently working toward a Ph.D. degree in automotive engineering at Kookmin University. His research interests include control methods for multiphase electrical machines, sensor-less control, and nonlinear control.

**Dong-Kil Kang** received a bachelor’s degree in computer science from Ulsan University, Ulsan, South Korea, in 2015. He is currently working toward a Ph.D. degree in automotive engineering at Kookmin University and works as a researcher at Korea Automotive Technology Institute (KATECH). His current research interests include advanced control of electric machines and electric vehicles.

**Doo-Il Son** received a bachelor’s degree in automotive engineering from Kookmin University, Seoul, South Korea, in 2016. He is currently working toward a Ph.D. in automotive engineering at Kookmin University’s Motor Control Lab. His research focuses on the control method for permanent magnet synchronous motors (PMSMs) and the design of electric machines for high efficiency and safety.

**Soon-Ho Kwon** received a B.S. degree in electrical engineering from Myongji University, Gyeonggi-do, South Korea in 2017, and a master’s degree in automotive engineering from Kookmin University in 2019. Currently, he is pursuing a Ph.D. degree in automotive engineering from Kookmin University, Seoul, South Korea. His research interests include power converter/inverter design and permanent magnet ac motor control.

**Geun-Ho Lee** received his B.S. and M.S. degrees in electrical engineering and his Ph.D. in automotive engineering in 1992, 1994 and 2010 from the Hanyang University, Seoul, South Korea. From 1994 to 2002, he joined the LG Industrial Research Institute, where he developed inverter system for elevators. Since 2011, he has been a professor in the department of automotive engineering at Kookmin University. His current research interests include advanced control of electric machines and electric vehicles.