Alleviation Technique for Thermal Concentration on Power Devices Driving a PMSM under Zero-Speed and High-Torque Condition

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This work is concerned with a technique to alleviate thermal concentration on specific switching devices that drive a permanent magnet synchronous motor (PMSM) under zero-speed and high-torque condition. In this condition, e.g., start or stop of an elevator or hill-start of an electric vehicle, a large DC current flows in the PMSM, and the heat generated in the specific switching devices is locally concentrated. The proposed technique uses a zero-sequence voltage in a three-level inverter, and the polarity of the zero-sequence voltage is switched according to the magnetic pole position of the PMSM. The proposed technique can change the current paths in the inverter, and the loss concentrations in specific devices can be alleviated. The simulation results show that the amplitude and the time ratio of the zero-sequence voltage that depend on the magnetic pole position of the PMSM affect the temperature rise of the power device with the maximum temperature. In the experiment, the effectiveness of the proposed technique is evaluated using a small power inverter. This three-level inverter consists of discrete power devices so that the surface temperature of each device can be observed with a thermal camera. The experimental results show that the temperature rise of the device with the maximum temperature is reduced by about 31%.

Keywords: power device temperature, PMSM, thermal concentration, zero-sequence voltage, zero speed, three-level inverter

1. Introduction

Recently, the energy saving of home appliances and industrial equipment has been promoted to solve environmental problems such as prevention of global warming. Permanent magnet (PM) motors have realized high efficiency drive and miniaturization by using permanent magnets with large magnetic flux density such as neodymium magnets, and their application ranges are expanded. Nowadays, the PM motors are used in wide fields which are home appliances such as refrigerators and air conditioners, industrial equipment such as electric cars and elevators, etc. On the other hand, there is a problem that the junction temperature of the power switching device increases at low-speed driving of electric cars and wind power generators. Under conditions where the inverter is driven at zero-speed with high-torque condition such as hill start of an electric vehicle or a train, starting and stopping of an elevator and pressing of the servo press equipment, a large DC current flows through the PM motor. The current flows only through the specific switching devices in the inverter corresponding to the magnetic pole position of the motor and heats them up instantly. This may decrease the life of the device or increase the size of the cooling system. Especially, in devices or power modules with large power density, the temperature of a specific chip may rise for a short time, and may cause a failure. The power devices have a concept called “power cycle” depending on the temperature rise and its times. It means the life time of the power device, which is determined by the bonding solder deterioration at the wire junctions or under the silicon chips. The life time of the devices decrease exponentially with increasing the temperature at the joints of the chips.

In order to reduce the heat generation of the power devices, some methods were reported such as estimating the heat generation and applying the active thermal control, controlling DC link voltage at low speed drive, controlling switching frequency at low speed drive. In modular multi-level converters, the method to reduce the thermal concentration by controlling the module inverters was reported. In power module, the ribbon bonding is applied to reduce the deterioration of the wire junction instead of wire bonding.

In this paper, the technique with a three-level inverter is considered to solve the problem of the power loss concentration in the specific power devices. The concentrated power losses are alleviated by actively using the zero-sequence voltage and changing the current path. The three-level inverters have many switching devices and the control is complicated. However, since the output voltages have many steps, they can reduce the switching loss, distortions of output voltage and output current, and electromagnetic noise. Recently, the power modules for the three-level inverter have been put to
practical use, and the application range has been expanded (17). The zero-sequence voltage is a common voltage given to each phase and has no influence on the line-line voltages. It is used for the improvement of the voltage utilization by adding of the third harmonics voltage, the reduction of leakage current (18), the sensor-less control of PM motor (19). In modular multilevel converters, it is used for the balance control of the capacitor voltages (20) and the current ripple reduction (21). In three-level inverters, the neutral point balance control using the zero-sequence voltage was widely studied (22)(23). In addition, as a method of reducing switching loss, the discontinuous PWM is well known as the example of effectively using the zero-sequence voltage (24)(25). The discontinuous PWM is also effective for reducing the heat concentration on the specific device at low speed operation (16)(20).

The authors proposed the alleviation technique for the heat concentration on specific switching devices which drive a PM motor in zero-speed and high-torque condition (27). The proposed technique uses a zero-sequence voltage in a three-level inverter, and the polarity of the zero-sequence voltage is switched according to the magnetic pole position of the PM motor. The authors reported that the proposed technique could alleviate loss concentration in the specific power devices by simulation (27).

In this paper, the effectiveness of the proposed technique is evaluated using a small power inverter (27). The three-level inverter consists of discrete power devices so that the surface temperature of each power device can be observed with a thermal camera. First, not only the power loss but also the temperature rise of each power device in the small power inverter are estimated by simulation. It is shown that the appropriate time ratio for the zero-sequence voltage that depends on the magnetic pole position of the PM motor is the effective of alleviating the heat concentration. The relationships between the temperature rise of the device with the maximum temperature, the balance of the charges supplied by the voltage sources and the amplitude of the zero-sequence voltage are shown. Furthermore, by experiments, the validity of the simulation and the effectiveness of the proposed technique are verified.

2. Principle of Heat Alleviating

2.1 System Configuration

Figure 1 shows a system configuration of the proposed inverter. In this paper, a three-level inverter is used and a PM motor is driven. The three-level inverter is composed of four switching devices and two clamp diodes in each phase. When the PM motor is rotated, the current flowing through each switching device in the inverter is switched by commutation. In this case, the loss generated at each switching device is approximately equalized. On the other hand, when the PM motor is driven under zero-speed and high-torque condition, the inverter continues to output a DC voltage. In this case, a large current flows only through specific switching devices and it causes a thermal concentration. In the proposed technique, the zero-sequence voltage \( V_0 \) is given to all the voltage references \( v_u^*, v_v^*, v_w^* \) derived by the general vector control in the control circuit. In particular, the feature of the proposed technique is to switch \( V_0 \) between positive and negative by changing the time ratio in consideration of the magnetic pole position of the PM motor.

When the PM motor is driven under zero-speed condition, the output currents of the inverter are DC values. The current value of each phase depends on the magnetic pole position of the PM motor. Here, the magnetic pole position \( \theta \) is defined as 0° where the U-phase current is the maximum value \( I_{\text{max}} \) and the V- and W-phase currents are \(-I_{\text{max}}/2\). Figure 2 shows the relationship between the magnetic pole position and the phase currents. The phase currents are given as follows.

\[
\begin{align*}
I_u & = I_{\text{max}} \cos \theta \\
I_v & = I_{\text{max}} \cos(\theta - 2\pi/3) \\
I_w & = I_{\text{max}} \cos(\theta + 2\pi/3)
\end{align*}
\]

As \( \theta \) increases from 0°, \( I_v \) and \( I_w \) decrease and \( I_u \) increases. When \( \theta = 30° \), \( I_u \) becomes zero and \( I_v \), \( I_w \) become \( \sqrt{3}I_{\text{max}}/2 \), \(-\sqrt{3}I_{\text{max}}/2\), respectively. Here, focusing on the current absolute value, the phase of the maximum current changes every 60°, and the current characteristic becomes similar every 30° periodically. Therefore, the proposed technique is evaluated for the \( \theta \) range from 0° to 30°. In this way, the effect can be applied to all \( \theta \) range from 0° to 360°, by considering symmetry because the zero-sequence voltage \( V_0 \) is a voltage given to each phase equally. In this paper, the temperature characteristics of the switching devices where \( \theta = 0° \) and 30° are evaluated.

2.2 Current Path at \( \theta = 0° \)

Figure 3 shows the characteristics of the voltage references when the zero-sequence voltage \( V_0 \) is added by the proposed technique under the condition that PM motor drives zero-speed and \( \theta = 0° \). In
zero-speed condition, the voltage references become DC value. Focusing on the U-phase, $S_{u1}$ turns on when the voltage reference $v^\text{uref}_u$ is larger than the carrier 1 and turns off when $v^\text{uref}_u$ is smaller than the carrier 1. $S_{u3}$ is complementary to $S_{u1}$. $S_{u2}$ always conducts and $S_{u4}$ does not conduct under the condition where $v^\text{uref}_u$ and the carrier 1 are compared. Similarly, $S_{v2}$ turns on when $v^\text{uref}_v$ is larger than the carrier 2 and turns off when $v^\text{uref}_v$ is smaller than the carrier 2. $S_{v4}$ is complementary to $S_{v2}$. $S_{v3}$ always conducts and $S_{v1}$ does not conduct under the condition where $v^\text{uref}_v$ and the carrier 2 are compared. The same switching operation applies to the V- and W-phases.

According to Fig. 3(a), when $V_0$ is zero, which is the conventional method, $v^\text{uref}_u$ is compared to the carrier 1, and $v^\text{uref}_v$ and $v^\text{uref}_w$ are compared to the carrier 2. Figure 4 shows the current flows at $\theta = 0^\circ$ with the conventional method. Under the condition of the zero-speed, since the induced voltage of the PM motor does not occur, the absolute value of the reference is small. Therefore, in the U-phase, $S_{u1}$ turns on for extremely short time, and the clamp diode $D_{up}$ conducts for most of the time. $S_{u2}$ always conducts. The current flowing from the U-phase to the motor is split into the V- and W-phases and returns to the inverter. In this case, $S_{v4}$ and $S_{w4}$ conduct for a short time, and the clamp diodes $D_{on}$ and $D_{on}$ conduct for most of time. Also, $S_{v3}$ and $S_{w3}$ always conduct. As a result, the conduction loss of $S_{u2}$ becomes extremely large, and the device temperature also becomes high.

Figure 3(b) is an example of adding a sufficiently large positive $V_0$ by the proposed technique. In this case, all voltage references are only compared with the carrier 1. Figure 5(a) shows the current path in the case of Fig. 3(b). In the proposed technique, since only $V_0$ is added, the line-line voltages do not change, and the currents flowing into the motor are the same as the conventional method. However, as shown in Fig. 5(a), the current paths in the inverter can be changed. In the U-phase, the conduction time of $S_{u1}$ is increased and that of $S_{u2}$ do not change. In the V- and W-phase, the current does not flow to $S_{u4}$ and $S_{u1}$, and flows to $D_{u1}$, $D_{u2}$, $D_{u3}$ and $D_{u4}$. And the conduction times of $S_{u3}$ and $S_{u3}$ are decreased. Thus, the current paths can be switched by adding $V_0$ to each phase in the three-level inverter. In this case, however, the temperature of $S_{u2}$ is also the highest.

Figure 3(c) is an example of adding a sufficiently large negative $V_0$ by the proposed technique. In this case, all voltage references are only compared with the carrier 2. Figure 5(b) shows the current path in the case of Fig. 3(c). In the U-phase, there are current paths in which $D_{up}$ and $S_{u2}$ conduct, and $D_{u3}$ and $D_{u4}$ conduct. In the V- and W-phase, the current always flows to $S_{v1}$, $S_{v3}$, $S_{v4}$, $D_{on}$ and $D_{on}$ conduct depending on the switching state. Under the condition of Fig. 3(c), it is possible to create the current path in which the current does not flow $S_{u2}$ as shown in Fig. 5(b). As the results, it is possible to reduce the loss of $S_{u2}$ where the conduction loss is the largest in the conventional method. In the proposed technique, the current path is changed by switching $V_0$ between positive and negative at a specific time ratio. This makes it possible to equalize the heat generated by each switching device.

### 2.3 Current Path at $\theta = 30^\circ$

Figure 6 shows the characteristics of the voltage references when the zero-sequence voltage $V_0$ is added by the proposed technique.
Fig. 7. Current flows with conventional method (θ = 30°)

Fig. 8. Current flows with the proposed technique (θ = 30°)

under the condition that PM motor drives zero-speed and θ is 30°. The relationship between each carrier and each voltage reference is the same as θ = 0°. According to Fig. 6(a), when \( V_0 \) is zero, which is the conventional method, \( v_{\text{uref}} \) is compared to the carrier 1, and \( v_{\text{aref}} \) is compared to the carrier 2. Figure 7 shows the current flows at θ = 0° with conventional method. When θ is 30°, the current paths in the U- and W-phase are the same as θ = 0°. However, in the V-phase, the current does not flow. In this case, since \( S_{u2} \) and \( S_{w3} \) always conduct, the conduction losses of these devices become large and the device temperatures also become high.

Figure 6(b) is an example of adding a sufficiently large positive \( V_0 \) by the proposed technique. In this case, all voltage references are only compared with the carrier 1. Figure 8(a) shows the current path in the case of Fig. 6(b). Also in this case, the current does not flow in the V-phase. The conduction time of \( S_{u3} \) is increased and the conduction time of \( S_{w2} \) is decreased as compared to the case of Fig. 7. Therefore, the loss of \( S_{w2} \) can be reduced. Thus, since the current paths are different depending on θ, the loss characteristics of the switching devices are also different. In the proposed technique, the current path is changed by switching the time ratio of the \( V_0 \) polarity depending on θ. This makes it possible to equalize the heat generated by each switching device at any θ condition.

3. Configuration of the Small Power Inverter

We verify the proposed technique using a small power inverter. Figure 9 shows the photograph of the main circuit of the small power three-level inverter which is used in the experiment. IGBTs (GT20J341; Toshiba, rated current: 20 A) and clamp diodes (FMX32S; Thinki semiconductor, rated current: 20 A) are used, respectively. Each device is fixed to the heat sink via the heat dissipation sheet (5580H; 3M). As the purpose is to evaluate the temperature of each device, discrete devices are used instead of IGBT modules which include IGBT and diode chips for each phase, and the rated values of each device are determined with enough margin for the motor load. Moreover, in order to observe the temperatures of each device with a thermal camera, wiring is taken so that the wires and the switching devices do not overlap and can be seen from the top. The thermal camera detects the infrared rays to measure the temperature. However, if the surface of the switching devices are glossy, the infrared emissivity is low. Therefore, the main circuit in Fig. 9 is coated with black paint to improve the accuracy of temperature detection.

In the experiment, the DC link voltage was 100 V (\( E = 50 \) V in Fig. 1), and the carrier frequency was 5 kHz. Moreover, the PM motor (TS4127; Tamagawa Seiki) was used. Table 1 shows the motor specifications. The PM motor was driven under zero-speed condition and the torque was applied. The surface temperatures of each switching device were evaluated one minute after the torque driving since the temperature was approximately saturated. The zero-sequence voltage \( V_0 \) was added +30 V and −30 V to the voltage reference by changing the time ratio. The ambient temperature at the experiment was 21.3°C, and was also used in the simulation.

Fig. 9. Photograph of the main circuit of the small power three-level inverter
4. Simulation Results of the Device Temperature Characteristic

4.1 Calculation of the Power Device Loss  In this section, the calculation method of the losses of each switching device in Fig. 1 is shown. $P_{SW}$ which is the switching loss of IGBT is expressed as the following equation using the collector-emitter voltage $V_{CE}$, the conduction current $I$, the turn-on time $t_{on}$, the turn-off time $t_{off}$ and the switching frequency $f$.

$$P_{SW} = \frac{1}{6} \times V_{CE} \times I \times (t_{on} + t_{off}) \times f \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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were taken from the data sheet.

Table 3 shows the junction temperatures calculation results of typical devices with conventional method when $\theta = 0 \degree$. In this case, the current condition was that the U-phase current was 6 A, and V- and W-phase currents were −3 A. The junction temperatures of $S_{u2}$, $D_{u3}$, $S_{u3}$ and $S_{w3}$ where the current flowed as shown in Fig. 4 increased. In particular, the temperature of $S_{u2}$ became 56.8°C and it was 35.5°C higher than the ambient temperature (21.3°C).

Figure 11 shows simulation results of the device temperature characteristics with the proposed technique at $\theta = 0 \degree$. The addition time ratio of negative zero-sequence voltage is used as a parameter. When the time ratio is 0%, $V_0$, which is added to the voltage references, is always 30 V. When the time ratio is 100%, −30 V is always added as $V_0$. Figure 11 shows only the temperatures of $S_{u2}$, $D_{u3}$ and $D_{u4}$ that increase significantly in temperature at $\theta = 0 \degree$. According to Fig. 11, when the time ratio is 69% (The zero-sequence voltages 30 V and −30 V correspond to 69% and 31%, respectively), the maximum temperature becomes minimum (48.5°C). In this case, the temperature rises by 27.2°C above the ambient temperature. Therefore, the temperature rise can be reduced by 8°C (about 23.4%) compared with conventional method of Table 3.

Table 4 shows the junction temperatures calculation results of typical devices with conventional method when $\theta = 30 \degree$. In this case, the current condition was that the U-, V-, W-phase currents were $3 \sqrt{3}$ A, 0 A and $−3 \sqrt{3}$ A, respectively. The junction temperatures of $S_{u2}$, $S_{u3}$ where the current flowed as show in Fig. 7 became 51.9°C and rose by 30.6°C above the ambient temperature (21.3°C). The appropriate time ratio is constant at 69%, and the maximum temperature became minimum (47.1°C). In this case, the temperature rises by 25.8°C above the ambient temperature. Therefore, the temperature rise can be reduced by 4.8°C (about 15.7%) compared with the conventional method of Table 4.

Table 4. Junction temperatures calculation results of typical devices with conventional method ($\theta = 30 \degree$)

| $S_{u2}$ | $D_{u3}$ | $S_{u3}$ |
|---|---|---|
| 32.2°C | 51.9°C | 32.4°C |

Figure 12 shows simulation results of the device temperature characteristics with the proposed technique at $\theta = 0 \degree$. When $\theta$ increases from 0° to 30°, the temperature of $S_{w3}$ rises significantly and temperature of $D_{u4}$ falls since the current paths are changed. Therefore, the maximum temperature becomes minimum at the intersection of the temperatures of $S_{u2}$ and $S_{w3}$ at the range where $\theta$ is large. According to Fig. 12, when the time ratio is 50%, the maximum temperature becomes minimum (47.1°C). In this case, the temperature rises by 25.8°C above the ambient temperature. Therefore, the temperature rise can be reduced by 4.8°C (about 15.7%) compared with the conventional method of Table 4.

Figure 13 shows the characteristics of the appropriate time ratio and the temperature rise of the power device with the maximum temperature in each magnetic pole position $\theta$.

![Fig. 12. Simulation results of the device temperature characteristics ($\theta = 0 \degree$)](image)

![Fig. 13. Characteristics of the appropriate time ratio and temperature rise of the power device with the maximum temperature in each magnetic pole position $\theta$](image)
30°, it becomes 50% independently of $V_0$. The reason why the characteristics change when $\theta$ is greater than about 15° is that the device with the maximum temperature is switched. When $V_0$ is ±20 V, the appropriate time ratio is 100% in the range where $\theta$ is small. This means that the temperatures of $S_2$ and $D_3$ in Fig. 11 have no intersection, and $S_2$ is the maximum temperature at all range. When $V_0$ is ±40 V, the appropriate time ratio is about 50% for any $\theta$. This means that the amount of the charge supplied from each of two DC link power supplies is almost equal. In other words, when the DC link part is composed of capacitors, the larger the amplitude of $V_0$, the less the voltage imbalance occurs even under long-time zero-speed conditions.

Figure 15 shows the characteristics of the temperature rise of the power device with the maximum temperature to the amplitude of $V_0$.

5. Experimental Results

The surface temperatures of each power device were measured by thermal camera (FLIR C2), and the conventional method and the proposed technique were evaluated. Since the IGBT device included the IGBT chips and the diode chips for the free wheeling diode, it was collectively evaluated as the IGBT device temperature. In the measurement, the motor torque was applied so that the current conditions were the same as in the simulation. The temperatures after driving for 1 minute under the same torque condition were measured, and after each measurement, the devices and the heat sink were sufficiently cooled before the next measurement. The ambient temperature during the experiments was 21.3°C.

5.1 Temperature Characteristics in Conventional Method

Figures 16, 17 and Table 5 show the current waveforms, the thermography of the main circuit and the surface temperatures of the typical devices with the conventional method at $\theta = 0°$, respectively. According to Fig. 16, the U-phase current which is about 6 A flows from the inverter to the PM motor. It is divided equally into the V- and W-phase, and the currents which are −3 A flow from the PM motor to the inverter. According to Fig. 17, the temperatures of the IGBT devices on the current path in Fig. 4 rise. Comparing the simulation results of Table 3 with the experimental results of Table 5, the temperatures of the experimental results are slightly lower than those of simulation results. This
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Fig. 18. Phase currents ($\theta = 30^\circ$)

Fig. 19. Thermography of the main circuit with the conventional method ($\theta = 30^\circ$)

Table 6. Experimental results of the surface temperatures of some major devices with the conventional method ($\theta = 30$ deg.)

| Device Type                  | Surface Temperature (°C) |
|------------------------------|--------------------------|
| Discrete IGBT ($S_u + D_u$)  | $27.6$                   |
| Discrete IGBT ($S_u + D_u$)  | $48.0$                   |
| Discrete IGBT ($S_u + D_u$)  | $24.2$                   |
| Discrete diode ($D_{up}$)    | $36.2$                   |

is because the temperatures measured in the experiment is the case temperatures of the devices, not the device junction temperatures. However, the temperature rise of each device shows qualitatively similar features to the simulation results.

Figures 18, 19 and Table 6 show the current waveforms, the thermography of the main circuit and the surface temperatures of typical devices with the conventional method at $\theta = 30^\circ$, respectively. According to Fig. 18, the current which is about 5.2 A ($\approx 3 \sqrt{3}$ A) flows from the inverter to the PM motor in the U-phase and returns from the PM motor to the inverter as the W-phase current. According to Fig. 19, the temperatures of the IGBT devices on the current path in Fig. 7 rise. Comparing the simulation results of Table 4 with the results of Table 6, the temperatures of the experimental results are slightly lower than those of simulation results due to the above-mentioned reason, same as in the case of $\theta = 0^\circ$.

5.2 Temperature Characteristics with the Proposed Technique

Figure 20 shows the characteristics of the device temperature with the proposed technique at $\theta = 0^\circ$ and it corresponds to the simulation results in Fig. 11. The experiment evaluated the temperatures using the additional time ratio of negative zero-sequence voltage as a parameter. $V_0$, which was 30 V or $-30$ V, was adjusted by the ratio in the period of 10 ms (which was 50 carrier period). The temperatures in experimental results are lower than those of the simulation results on the whole due to the above-mentioned reason. According to Fig. 20, the maximum temperature becomes minimum (41.5°C) and the temperature rise from the atmospheric temperature is 20.2°C when the ratio of the additional negative zero-sequence voltage is 90%. The maximum temperature with the proposed technique is reduced by 9.1°C and the temperature rise is reduced by about 31.1% when compared with the maximum temperature of 50.6°C (the temperature rise is 29.3°C) of the conventional method (Table 5). This confirms that the proposed technique is effective. Figure 21 shows the thermography of the main circuit with the proposed technique when the ratio of the additional negative zero-sequence voltage is 90% ($\theta = 0^\circ$). When the proposed technique is used, the device temperatures are dispersed and the maximum temperature is reduced as compared with that with the conventional method.

Figure 22 shows the characteristics of the device temperature with the proposed technique at $\theta = 30^\circ$. In this case, the temperatures in experimental results are also lower than those of the simulation results on the whole due to the above-mentioned reason. According to Fig. 22, the maximum temperature becomes minimum (45.6°C) and the temperature rise from the atmospheric temperature is 24.3°C when the ratio of the additional negative zero-sequence voltage is 50%. The maximum temperature with the proposed technique is reduced by 3.2°C and the temperature rise is reduced by about 11.6% when compared with the maximum temperature of
The feature of the proposed technique is to use a zero-sequence voltage to drive a PM motor in zero-speed and high-torque condition. The additional negative zero-sequence voltage is 50% at \( \theta = 30^\circ \) when the ratio of the additional negative zero-sequence voltage is 30% (\( \theta = 30^\circ \)).

The effectiveness of the proposed technique are confirmed from the aspect of the experiment. The experiment was conducted at 0° and 30° magnetic pole positions. The proposed technique has increased the device temperatures. However, when the magnetic pole position was 0°, the maximum temperature could be minimized by setting the ratio of the additional negative zero-sequence voltage to 90%. In this case, the temperature rise of the device with the maximum temperature could have been reduced by about 31.1% compared with that with the conventional method. When the magnetic pole position was 30°, the maximum temperature could be minimized by setting the ratio of the additional negative zero-sequence voltage to 50%. In this case, the temperature rise of the device with the maximum temperature could have been reduced by about 11.6% compared with that with the conventional method.

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