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Experimental investigatopn of temperature-induced performance degradation in BLDC motors for electric vehicle applications

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Abstract

The performance of Brushless Direct Current (BLDC) motors in electric vehicle applications is significantly affected by thermal operating conditions; however, experimental studies that directly evaluate temperature-induced performance degradation under real prototype operation remain limited. This study aims to experimentally evaluate the effect of operating temperature on the torque and power characteristics of a BLDC motor integrated into an electric vehicle prototype developed in Bali Land Transportation Polytechnic, Bali. The motor was tested under controlled conditions at rotational speeds ranging from 750 to 2000 rpm. Electrical current, operating temperature, torque, and output power were measured directly, while mechanical output power was calculated using rotational dynamics principles. The results showed that increasing motor speed caused a continuous rise in current and operating temperature, from 34.8 °C at 750 rpm to 87.3 °C at 2000 rpm. Mechanical output power increased with speed and reached a maximum value of 7.13 HP within the range of 1250–1500 rpm, before decreasing at higher speeds despite further increases in current and angular velocity. This reduction was accompanied by a significant decrease in torque, indicating thermally induced electromagnetic performance degradation. The findings identify an optimal operating region limited by temperature and highlight the importance of thermal management for maintaining performance and reliability in electric vehicle propulsion systems.

Keywords:
BLDC motor; electric vehicle; thermal effects; torque degradation; power performance

1 Introduction

The development of Electric Vehicles (EVs) has emerged as a strategic solution to reduce dependence on fossil fuels and to mitigate exhaust gas emissions in the transportation sector. Compared to conventional internal combustion engine vehicles, EVs offer higher energy efficiency and lower environmental impact, making them a key component in sustainable transportation systems [1]. Consequently, the reliability and performance of electric propulsion systems have become critical factors influencing the widespread adoption of EV technologies [2].

Electric motors play a fundamental role in determining vehicle performance, including acceleration, maximum speed, and energy efficiency. Among various motor types, Brushless Direct Current (BLDC) motors are widely applied in electric vehicle systems due to their high-power density, high efficiency, and precise speed control capability [3]. In addition, BLDC motors offer improved reliability and longer service life due to the absence of mechanical brushes. However, despite these advantages, their performance is highly sensitive to operating conditions, particularly thermal effects, which significantly influence both electrical and mechanical characteristics [4].

During operation, BLDC motors generate heat due to multiple loss mechanisms, including copper losses in stator windings, magnetic core losses, as well as mechanical and electronic losses. Copper losses, which follow Joule's law, increase proportionally to the square of the electric current and represent a dominant source of heat generation in electric machines [7]. As motor rotational speed increases, the required current also rises, leading to intensified heat accumulation within the motor. Elevated operating temperatures increase winding resistance and reduce magnetic flux density in permanent magnet motors, resulting in decreased torque and output power [5], [6]. In addition, prolonged exposure to high temperatures may lead to partial demagnetization of permanent magnets, further degrading motor performance and efficiency.

From a system perspective, BLDC motor performance is governed by the interaction between electrical, mechanical, and thermal parameters. Electromagnetic torque is proportional to stator current, while mechanical output power is determined by the product of torque and angular velocity. Electrical input power depends on voltage and current, and overall efficiency is defined as the ratio of mechanical output to electrical input power [15][16][18]. These relationships indicate that thermal conditions play a crucial role in determining the effectiveness of energy conversion and overall motor performance.

Previous studies have reported that increasing motor speed leads to higher current consumption and temperature rise, which negatively affects efficiency and output performance [7][8]. Consequently, thermal management has been widely recognized as a critical factor in maintaining motor reliability and extending operational lifespan. The implementation of cooling systems has been shown to reduce operating temperature and improve motor efficiency [9], while integrated thermal–electromagnetic analysis has been emphasized as essential in motor design optimization [10].

However, a critical limitation remains in the existing literature. Most prior studies are based on numerical simulations or controlled laboratory experiments that analyze standalone BLDC motors under simplified conditions. Such approaches do not fully represent real operating conditions in electric vehicle systems, where electrical, mechanical, and thermal interactions occur simultaneously. Moreover, there is a lack of experimental studies that provide an integrated analysis of motor speed, current, temperature, torque, and output power within an actual electric vehicle prototype, particularly in applied and vocational-based research environments. In addition, previous studies rarely identify clear temperature-dependent operational limits that define optimal and critical performance regions of BLDC motors. This gap limits the practical applicability of existing findings for real-world electric vehicle development.

To address these gaps, this study proposes a comprehensive experimental investigation of BLDC motor performance under real operating conditions in an electric vehicle prototype. The novelty of this research lies in: (1) the implementation of an integrated experimental framework that simultaneously measures motor rotational speed, electric current, operating temperature, torque, and output power within a unified system; (2) the analysis of thermal effects on motor performance based on direct experimental data rather than simulation; and (3) the identification of a temperature-dependent operational threshold that defines the optimal performance region of the BLDC motor.

Therefore, this study aims to experimentally analyze the influence of operating temperature on the performance of a BLDC motor integrated into an electric vehicle prototype developed at Politeknik Transportasi Darat Bali (Poltrada Bali). The results are expected to provide practical insights into thermally induced performance degradation and contribute to the development of more efficient, reliable, and thermally optimized electric vehicle propulsion systems.

2 Method

A quantitative experimental approach was adopted in this study to investigate the influence of operating temperature on the performance of a BLDC motor through direct testing and measurement. Experimental research is appropriate for identifying cause–effect relationships by controlling specific variables and observing their impact on dependent variables [19]. A quantitative approach was selected because the data obtained consist of numerical measurements, including electric current, motor operating temperature, and rotational speed, which were subsequently analyzed using mathematical equations and graphical representations to describe the relationships among variables [20].

The research was conducted at the laboratories of Politeknik Transportasi Darat Bali and PGRI 2 Badung from February to July 2023. The object of this study was a BLDC motor used as the primary propulsion unit in an electric vehicle prototype developed at Poltrada Bali. The tested motor has a nominal power rating of 3000 W and is operated using an inverter with electronic commutation. Structurally, the motor is equipped with an aluminum heatsink and outer casing that function as both a protective enclosure and a passive cooling system to dissipate heat during operation. The stator consists of 12 poles made of electrical steel, with each pole wound using 0.8 mm diameter enameled copper wire arranged in a parallel configuration. The rotor is composed of a shaft, a magnetic housing, and 20 permanent magnets. This configuration enables efficient electromagnetic energy conversion required for electric vehicle propulsion.

Due to the limited availability of manufacturer specifications, detailed parameters such as rated voltage, rated current, and rated torque are not fully specified in this study. However, the available configuration and experimental setup are sufficient to represent the motor behavior under real operating conditions. The research variables were classified into three categories: independent, dependent, and controlled variables [21]. The independent variable was the motor rotational speed (rpm), which was varied at 750, 1000, 1250, 1500, 1750, and 2000 rpm. The dependent variables included motor operating temperature (°C) and BLDC motor performance parameters, specifically torque, output power, and efficiency. The controlled variables consisted of supply voltage, ambient testing conditions, and the motor cooling system.

The experimental setup consisted of a dynamometer used to regulate and measure motor rotational speed, a digital ammeter to measure electric current, and a thermal camera to measure motor operating temperature using a non-contact method. The thermal camera was positioned at a fixed distance from the motor surface to ensure consistent measurement conditions and to allow real-time observation of temperature distribution on the motor housing. This method provides high measurement accuracy and enables detailed thermal mapping of the motor surface [22]. The overall experimental configuration, including instrument placement and data acquisition flow, is illustrated in Fig. 1. The actual experimental setup, including the placement of measurement instruments used during the tests, is shown in Fig. 2.

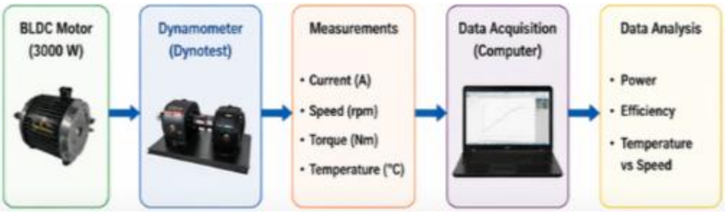


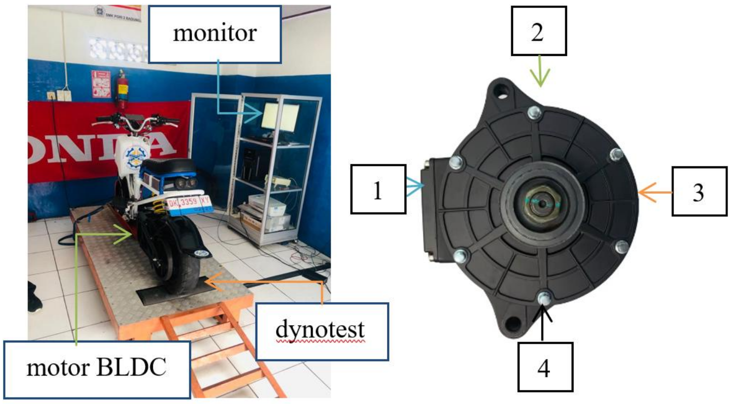
Fig. 1. Data acquisition flow

The experimental procedure was conducted in several stages. First, the electric vehicle prototype was prepared, and the BLDC motor system was verified to operate properly. Second, the motor rotational speed was set at predetermined values (750, 1000, 1250, 1500, 1750, and 2000 rpm) using a dynamometer. Third, the motor was operated continuously at each speed level until a thermally stable condition was reached. Subsequently, electric current and motor operating temperature were measured and recorded. Each test was repeated three times to ensure data consistency and reliability, and the results were averaged for further analysis.

The experimental procedure followed standard electric motor testing practices as described in IEEE standards [18]. Data analysis was performed using both descriptive and quantitative approaches. Electrical input power was calculated as the product of voltage and current, while mechanical output power was determined based on the product of torque and angular velocity derived from rotational speed [15], [16]. BLDC motor efficiency was calculated as the ratio of output power to input power [12]. The analysis results were presented in the form of tables and graphs to illustrate the relationships among motor speed, operating temperature, and performance characteristics. Interpretation of the results was carried out by comparing the findings with relevant previous studies.

3 Results

The results of the BLDC motor testing conducted on the electric vehicle prototype developed at Politeknik Transportasi Darat Bali indicate a strong relationship between motor rotational speed, electric current, operating temperature, and motor performance in terms of torque and output power. The data acquisition process is shown in Fig. 2.



(a) (b)

Fig. 2. Data acquisition setup for BLDC motor testing in an electric vehicle prototype: (a) experimental setup, (b) temperature measurement positions

The experimental tests were performed at rotational speed variations ranging from 750 to 2000 rpm under controlled supply voltage and environmental conditions. The measured parameters included motor operating temperature, electric current, output power, and torque. Each test was conducted three times for every operating condition to ensure data reliability, and the values presented in Table 1 represent the average results of these repeated measurements. The experimental data obtained from the BLDC motor testing are summarized in Table 1.

Table 1. Experimental results of BLDC motor performance

RPM	Temperature (°C)	Current (A)	Power (HP)	Torque (Nm)
750	34.8	4.4	3.9	37.37
1000	43.7	5.2	4.9	34.51
1250	52.6	6	6	33.51
1500	63.5	6.8	6.4	33.87
1750	74.4	7.7	6.7	27.31
2000	87.3	8.7	5.5	19.38

Based on the experimental results, increasing the motor rotational speed from 750 rpm to 2000 rpm caused the electric current to rise from 4.4 A to 8.7 A. This increase in current was accompanied by a significant rise in motor operating temperature, from 34.8 °C at 750 rpm to 87.3 °C at 2000 rpm. These results indicate that higher motor rotational speeds directly increase the thermal load experienced by the BLDC motor.

The mechanical output power of the motor increased with rotational speed until reaching a maximum value in the range of 1500–1750 rpm. At 1500 rpm, the output power was recorded at 6.4 HP, while at 1750 rpm it reached 6.7 HP. However, at the highest speed of 2000 rpm, the output power decreased to 5.5 HP, despite continuous increases in electric current and operating temperature. This phenomenon indicates that, at high rotational speeds, the motor is no longer able to efficiently convert electrical energy into mechanical energy.

Motor torque exhibited a decreasing trend with increasing rotational speed and operating temperature. The highest torque was obtained at 750 rpm, reaching 37.37 Nm, and gradually decreased to 19.38 Nm at 2000 rpm. The significant reduction in torque at high rotational speeds suggests a degradation of the motor's electromagnetic capability due to thermal effects.

3.1 Relationship between motor speed and operating temperature

The experimental results show that increasing the BLDC motor speed from 750 rpm to 2000 rpm led to an increase in operating temperature from 34.8 °C to 87.3 °C. This relationship is illustrated in Fig. 3. In this figure, the horizontal axis (x-axis) represents motor rotational speed (rpm), while the vertical axis (y-axis) represents operating temperature (°C). The temperature rise exhibits an approximately linear trend with increasing motor speed.

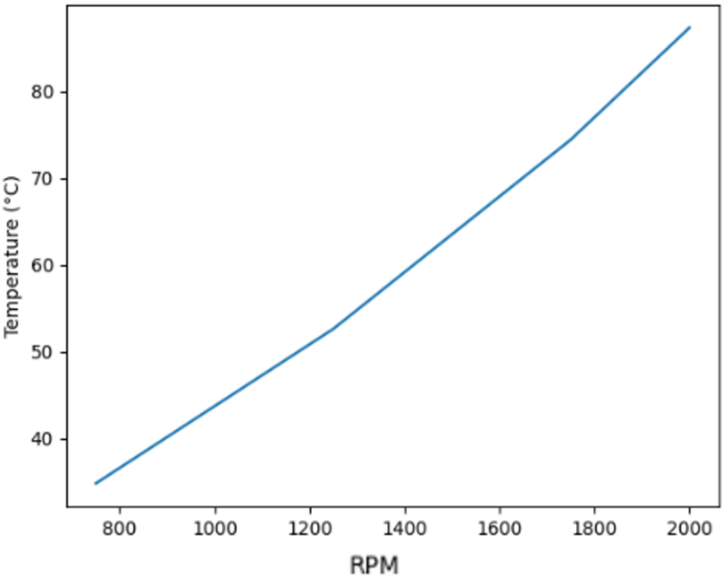


Fig. 3. Thermal response of the motor under varying rotational speeds

From a theoretical perspective, this temperature increase is primarily caused by rising copper losses in the stator windings, which follow Joule's law. As the current increased from 4.4 A to 8.7 A, copper losses rose quadratically, directly contributing to the significant increase in motor operating temperature. This trend is consistent with previous studies [7][8], which report that increased current at higher speeds leads to significant thermal accumulation in BLDC motors.

3.2 Mechanical output power calculation

The motor angular velocity was calculated using rotational mechanics principles (Eq. (1)) [16].

$$\omega = \frac{2\pi \times RPM}{60} \tag{1}$$

For 750 rpm, it can be calculated as Eq. (2).

$$\omega = \frac{2\pi \times 750}{60} = 78.54\, rad/s \tag{2}$$

The mechanical output power was calculated using Eq. (3).

$$P_{out} = T \times \omega \tag{3}$$

Thus, at 750 rpm, it can be calculated as Eq. (4).

$$P_{out} = 37.37 \times 78.54 = 2935.03\ W \tag{4}$$

When converted to horsepower, this results in the Eq. (5).

$$P_{out} = \frac{2935.03}{745.7} = 3.94\ HP \tag{5}$$

This calculated value closely matches the experimentally measured output power, indicating good consistency in the experimental data. Similar calculations were performed for all speed variations. The results show that mechanical output power increased with speed, reaching a maximum value of 7.13 HP at 1500 rpm, before decreasing at higher rotational speeds. Table 2 presents the overall calculation results.

Table 2. Mechanical output power calculation results

RPM	Torsi (Nm)	ω (rad/s)	P_{out}(W)	P_{out}(HP)
750	37.37	78.54	2934.6	3.93
1000	34.51	104.72	3614.7	4.85
1250	33.51	130.90	4386.2	5.88
1500	33.87	157.08	5319.4	7.13
1750	27.31	183.26	5004.8	6.71
2000	19.38	209.44	4058.9	5.44

3.3 Relationship between motor speed and output power

The relationship between motor rotational speed and output power is presented in Fig. 4. The x-axis represents motor rotational speed (rpm), while the y-axis represents output power (HP). The results show that output power increases with rotational speed up to 1500 rpm and then decreases at higher speeds. This behavior is consistent with [8], which states that thermal losses at high temperatures reduce effective energy conversion efficiency.

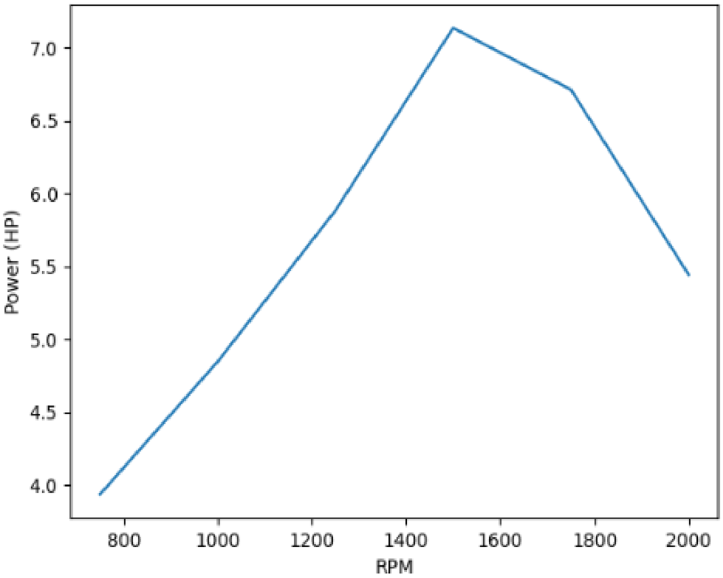


Fig. 4. Mechanical power output as a function of rotational speed

3.4 Effect of temperature on BLDC motor torque

Theoretically, BLDC motor torque is directly proportional to the electric current flowing through the stator windings [3]. However, the experimental results show that an increase in current is not always accompanied by an increase in torque. In this study, although the current increased from 6.8 A at 1500 rpm to 8.7 A at 2000 rpm, the torque decreased significantly from 33.87 Nm to 19.38 Nm. The relationship between torque and temperature is shown in Fig. 5. The x-axis represents operating temperature (°C), while the y-axis represents torque (Nm).

The results indicate that increasing temperature leads to a significant reduction in torque. This finding is consistent with [5] and [6], which report that increased temperature reduces magnetic flux density and torque constant.

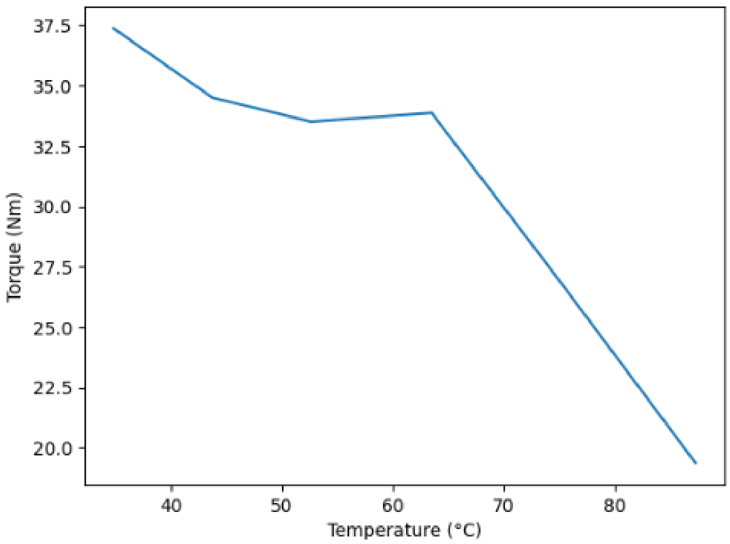


Fig. 5. Dependency of motor torque output on operating temperature

3.5 Power degradation due to thermal effects

The reduction in output power at high rotational speeds indicates the dominance of thermal and electromagnetic losses. At elevated operating temperatures, copper losses and magnetic core losses increase significantly, thereby reducing the energy conversion efficiency of the BLDC motor [8]. Furthermore, exposure to high temperatures (approaching 90 °C in this study) may lead to partial demagnetization of permanent magnets, which contributes to reductions in torque and output power [6]. This behavior aligns with previous findings, confirming that temperature is a critical limiting factor in BLDC motor performance.

3.6 Implications for electric vehicle applications

The findings of this study highlight the critical importance of controlling BLDC motor operating temperature in electric vehicle applications. Inadequate thermal management can lead to performance degradation and reduced motor lifespan [9]. Based on the experimental results, the optimal operating region for the BLDC motor lies within the speed range of 1250–1500 rpm, where relatively high output power is achieved while the operating temperature remains within acceptable limits. These findings are consistent with [10], which emphasizes that the integration of electromagnetic and thermal analyses is a key factor in the design and operation of BLDC motors for electric vehicle applications.

4 Discussion

The results of this study clearly demonstrate that the performance of the BLDC motor used in the electric vehicle prototype is strongly influenced by the complex interaction between motor speed, electric current, and thermal conditions. Although an increase in motor speed is theoretically expected to enhance output power, this improvement is constrained by thermal effects that emerge during continuous operation. These results indicate that BLDC motor performance is not solely determined by electrical and mechanical parameters but is also highly dependent on the stability of its thermal characteristics.

The observed increase in motor operating temperature with rising rotational speed is a direct consequence of increased copper losses in the stator windings. According to Joule's law, copper losses increase quadratically with electric current. In this study, the current nearly doubled from low-speed to high-speed operation, resulting in a substantial increase in heat dissipation. Previous studies [5], [12] have reported that, in permanent magnet motors, elevated winding temperatures lead to increased stator resistance, which further amplifies losses and may trigger thermal runaway if not properly controlled.

The reduction in torque observed with increasing operating temperature indicates a degradation of the motor's electromagnetic characteristics. Theoretically, BLDC motor torque is proportional to the stator current, as stated in [3]. However, the present results show that this relationship is valid only within a limited temperature range. When the motor operating temperature exceeds a certain threshold, the torque constant can no longer be considered constant. This behavior is primarily attributed to a reduction in permanent magnetic flux density due to thermal effects, as reported in [5]. Consequently, increases in electric current fail to produce proportional torque gains and may even result in significant torque reduction.

The decline in output power at high rotational speeds, despite increasing angular velocity, is a strong indicator of the dominance of internal motor losses. Mechanical output power is defined as the product of torque and angular velocity. In this study, although angular velocity increased linearly with motor speed, the substantial torque reduction at elevated temperatures caused the output power to reach a maximum at medium speeds before decreasing at higher speeds. This observation is consistent with [8] which emphasizes that, under high-temperature conditions, copper losses and magnetic core losses become the primary limiting factors of BLDC motor performance, leading to a significant reduction in energy conversion efficiency.

In addition to copper losses, high operating temperatures may also induce partial degradation of permanent magnets. According to [6] exposure of permanent magnets to elevated temperatures can result in both reversible and irreversible flux reduction, depending on the temperature level and exposure duration. In the present study, operating temperatures approaching 90 °C at high rotational speeds are likely to cause temporary flux weakening, which directly contributes to the observed reductions in torque and output power. These findings highlight that the thermal limit of the BLDC motor is a critical factor that must be carefully considered in electric vehicle applications.

From an electric vehicle drivetrain perspective, these results have significant practical implications. EVs require stable motor performance under a wide range of operating conditions, including high-speed and high-load scenarios. However, this study demonstrates that operating a BLDC motor at high speeds without adequate thermal management can degrade performance and accelerate component deterioration. This finding aligns with [9], which identifies cooling system failure as a major cause of reduced efficiency and shortened lifespan in BLDC motors.

Furthermore, the results reinforce the importance of adopting an integrated electromagnetic–thermal design approach in the development of BLDC motors for EVs. As emphasized in [10], motor performance optimization cannot rely solely on electromagnetic considerations but must also account for temperature distribution and heat dissipation mechanisms. In the context of the Poltrada Bali electric vehicle prototype, these findings provide a foundation for improving cooling system design or defining optimal motor operating strategies.

Overall, this discussion confirms that operating temperature is a primary limiting factor in BLDC motor performance for electric vehicle applications. The observed reductions in torque and output power at high speeds are not merely due to mechanical design limitations but arise from complex interactions between electrical losses, permanent magnet degradation, and insufficient thermal management. Therefore, this study contributes to a deeper understanding of BLDC motor performance degradation mechanisms and strengthens existing evidence regarding the critical role of thermal management in electric vehicle propulsion systems.

5 Conclusions

This study experimentally investigated the effect of operating temperature on the performance of a BLDC motor in an electric vehicle prototype. The results demonstrate that increasing motor speed leads to higher current consumption and a significant rise in operating temperature, which directly affects motor performance. An optimal operating region was identified within the speed range of 1250–1500 rpm, where the motor achieves maximum output power under relatively stable thermal conditions. Beyond this range, further increases in temperature result in a noticeable reduction in torque and output power, indicating thermally induced performance degradation. These findings confirm that operating temperature is a critical factor limiting BLDC motor performance. Therefore, effective thermal management and proper determination of operating conditions are essential to maintain efficiency, reliability, and performance in electric vehicle applications.

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