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Energy Efficiency and Performance of PMSM Drives in Electric Vehicles under Variable Loads

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ABSTRACT

Improving electric vehicle energy efficiency is essential for extending driving range and reducing battery energy consumption. However, the performance of Permanent Magnet Synchronous Motor (PMSM)-based powertrains varies with operating speed and load, while experimental evidence identifying optimal operating regions through real-time measurements remains limited. This study evaluates the performance and energy efficiency of a PMSM-based electric vehicle powertrain under varying speed and load conditions using a real-time monitoring system. Experiments were conducted at speeds of 10–40 km/h and loads of 50–200 kg by measuring voltage, current, power, efficiency, and specific energy consumption. The results show that efficiency increases significantly from approximately 66% at low speeds to over 90% at higher speeds, while specific energy consumption decreases from 118 Wh/km to approximately 60 Wh/km, demonstrating improved energy utilization. Load variation has a relatively minor effect on efficiency but increases current and power demand. Efficiency-gradient analysis indicates a declining rate of improvement at higher speeds, suggesting saturation behavior and an optimal operating region. Measurement validation produces errors below 5%, confirming data reliability. Overall, medium-to-high-speed operation provides the most energy-efficient region, offering useful insights for powertrain optimization, energy-management strategies, battery utilization, and improved electric vehicle driving range.

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1. INTRODUCTION

The rapid development of electric vehicles (EVs) has become an important part of the transition toward sustainable transportation systems[1]. offering benefits such as reduced greenhouse gas emissions[2] lower noise pollution[3], higher energy [4]. and reduced dependence on fossil fuels [5]. Achieving these benefits strongly depends on the efficiency and reliability of the electric drivetrain, which directly determines overall vehicle performance [6]. Among various electric propulsion technologies, the Permanent Magnet Synchronous Motor (PMSM) has been widely adopted due to its high efficiency [7], high power density[8], and fast dynamic response [9]. Despite these advantages, PMSM performance is strongly influenced by operating conditions, particularly variations in speed and mechanical load [10]. Conventional theoretical analyses may not fully capture these dynamic operating conditions, potentially causing discrepancies between predicted and experimentally observed performance [11][12]. Moreover, the interaction between the energy storage system and electric motor [13][14], significantly affect cost[15], efficiency[16], driving range[17], and overall vehicle performance[18][19]. However, the actual performance of PMSM-based systems remains highly dependent on operational conditions that are not always adequately represented in theoretical models.

One of the main challenges in EV drivetrain development is the gap between ideal and real-world performance[20]. While system efficiency can theoretically be calculated based on the ratio of input to output power, practical systems are affected by various non-ideal factors, including conduction losses in semiconductor devices[20][21], switching losses in inverters[22], core and copper losses in electric motors[23], and the influence of dynamic load conditions[24]. Moreover, energy consumption characteristics in EVs are determined not only by motor efficiency but also by the interaction between the battery system[25], controller, and vehicle operating profile[26]. The lack of experimental data that integrates these parameters under real operating conditions remains a significant limitation in developing accurate and representative performance models.

Previous studies have investigated PMSM performance in EV applications using various approaches, including mathematical modeling, simulation-based analysis [27], and limited experimental testing. Although simulation-based studies have reported high PMSM efficiency under specific operating conditions, they often overlook comprehensive load variations [28]. Experimental studies have attempted to address this limitation; however, they generally focus on individual operating parameters, such as no-load and on-load conditions, speed–efficiency characteristics, or energy consumption under steady-state conditions [29], Furthermore, existing experimental approaches have not sufficiently integrated real-time monitoring systems capable of simultaneously capturing dynamic variations in electrical parameters under different speed and load conditions [30]. The accuracy and validation of measurement systems are also frequently overlooked, despite their importance in ensuring reliable experimental data. Therefore, a specific research gap remains in the comprehensive experimental characterization of PMSM performance that simultaneously integrates speed and load variations, real-time electrical parameter monitoring, specific energy consumption, and measurement validation within a unified experimental framework.

The main objective of this study is to comprehensively evaluate the performance and energy efficiency of a PMSM-based electric vehicle drivetrain under varying speed and load conditions. Specifically, this study aims to: (1) analyze the relationship between vehicle speed and drivetrain efficiency, and (2) evaluate the effect of load variation on power consumption and system efficiency. The key contributions of this study are the integration of real-time experimental monitoring with specific energy consumption (Wh/km) analysis to characterize energy utilization under different operating conditions, and the application of efficiency-gradient analysis to identify the optimal operating region of the PMSM-based drivetrain. Furthermore, measurement validation using reference instruments is incorporated to ensure the reliability of the experimental data. These contributions provide a practical basis for improving the energy efficiency, performance evaluation, and operational optimization of PMSM-based electric vehicle drivetrain systems.

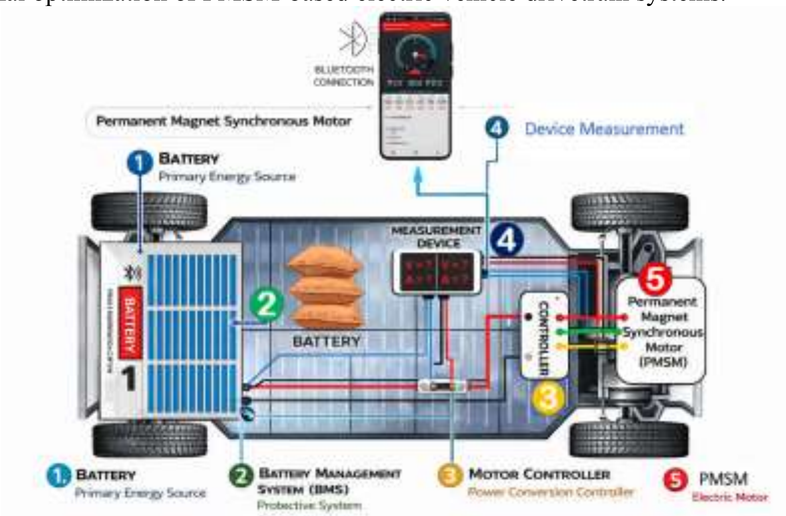

Figure 1. Schematic Diagram of Electric Vehicle Testing Setup

2. METHOD

This study was conducted by designing a PMSM-based electric vehicle testing system, as illustrated in Figure 1, consisting of a battery as the primary energy source, a Battery Management System (BMS) for protection, a motor controller for power conversion regulation, a Permanent Magnet Synchronous Motor (PMSM) as the propulsion unit, and a real-time monitoring-based measurement system to acquire electrical parameters directly during operation. The system was developed to evaluate the performance and energy efficiency of the electric vehicle under varying operating conditions, particularly changes in speed and load.

The first stage of the experiment involved testing under variations of two main parameters, namely vehicle speed and load. The vehicle speed was set at four levels: 10 km/h, 20 km/h, 30 km/h, and 40 km/h. The load was varied using additional mass in the form of sandbags with values of 50 kg, 100 kg, 150 kg, and 200 kg. For each combination of these conditions, electrical parameters such as DC voltage and DC current were measured, along with derived parameters including power and system efficiency. Measurements were carried out in real time using sensors integrated with the monitoring system, ensuring that the collected data accurately represent actual operating conditions. The input electrical power of the system was calculated based on the fundamental relationship between voltage and current, expressed as follows[31]:

$$P_{in} = V \times I \tag{1}$$

The input power P_{in} is defined as the electrical input power in watts (W), where V represents the DC voltage (V) and I denotes the DC current (A). This parameter serves as the fundamental basis for all energy analyses conducted in this study.

In the second stage, the efficiency of the PMSM-based drivetrain system is determined based on the ratio between output power and input power, which is generally expressed as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{2}$$

In the experimental implementation, efficiency is also analyzed in terms of overall system performance by comparing effective energy output to input energy. To identify the effect of speed on efficiency, efficiency values under each load condition are grouped based on identical speed levels, and the average efficiency is calculated using:

$$\bar{\eta}v = \frac{1}{n}\sum_{i=1}^{n} \eta_i \tag{3}$$

Where $\bar{\eta}v$ represents the average efficiency at a specific speed, and n is the number of load variations. This approach enables the identification of general efficiency trends as a function of vehicle speed. Furthermore, a similar analysis is conducted for electrical power, where power values under each load condition are grouped according to speed levels and averaged accordingly [32]:

$$\bar{P}v = \frac{1}{n}\sum_{i=1}^{n} P_i \tag{4}$$

This approach is employed to evaluate the system power requirement as a function of speed, denoted as $\bar{P}v$, enabling a quantitative analysis of the relationship between energy consumption and overall system performance.

In the third stage, the energy efficiency of the electric vehicle is evaluated in terms of specific energy consumption, defined as the energy consumed per unit distance traveled[33]. The specific energy is calculated as:

$$E_s = \frac{P_{in} \times t}{d} \tag{5}$$

or in a more general form:

$$E_s = \frac{E}{d} \tag{6}$$

where E_s represents the specific energy in Wh/km, E is the total energy consumed, and d is the travel distance of the vehicle. This parameter provides a more representative measure of electric vehicle efficiency under real operating conditions. The specific energy values are subsequently averaged with respect to speed to identify the most efficient operating conditions.

In the fourth stage, the validity of the obtained data is assessed through a measurement validation process by comparing the results from the real-time monitoring system with standard reference instruments. The percentage error is calculated using the following equation[34] ;

$$Error(\%) = \left|\frac{X_{meas} - X_{ref}}{X_{ref}}\right| x100\% \tag{7}$$

where X_{meas} is the measured value and X_{ref} f is the reference value. This process ensures that all parameters used in the analysis have a scientifically acceptable level of accuracy.

In the fifth stage, an analytical approach is conducted to evaluate the influence of speed and load on system efficiency using functional relationships, expressed as $\eta = f(v)$ for speed and $\eta = f(m)$ for load. To understand the dynamics of efficiency variation, the rate of efficiency improvement between speed intervals is calculated using[35]:

$$\Delta\eta = \eta_{i+1} - \eta_i \tag{8}$$

This analysis provides insight into the speed intervals that yield the most significant efficiency improvements. Furthermore, the sensitivity of efficiency to speed variation is analyzed using the efficiency gradient, expressed as:

$$\frac{d\eta}{dv} \approx \frac{\Delta\eta}{\Delta v} \quad (9)$$

which indicates the magnitude of efficiency change for each unit increase in speed. As a final stage, the relationship between efficiency and speed is modeled using a linear regression approach, expressed as[36]:

$$\eta = av + b \quad (10)$$

where a represents the efficiency growth coefficient with respect to speed, and b is a constant. This model is utilized to identify the overall trend and to provide a predictive approximation of the PMSM system performance under varying operating conditions.

3. RESULTS AND DISCUSSION

This section presents the experimental results and performance analysis of the PMSM-based electric vehicle drivetrain under variations in speed (10–40 km/h) and load (50–200 kg), using a real-time monitoring system.Fig. 1 illustrates the relationship between DC power and variations in speed and load in the PMSM drivetrain system. It can be observed that the DC power increases significantly with increasing vehicle speed, rising from approximately ±1100 W at 10 km/h to more than 2500 W at 40 km/h. In addition, higher load levels also result in increased power consumption at each speed level, with the 200 kg load consistently producing the highest power values. This pattern indicates that the system's energy demand is predominantly influenced by vehicle speed, while load acts as a secondary factor that amplifies power consumption through increased motor torque requirements.

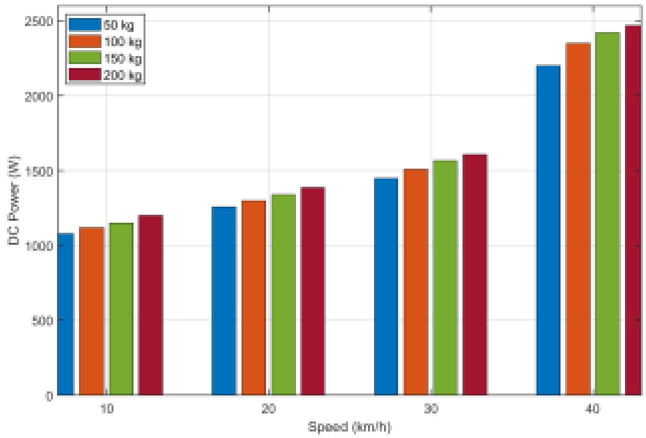

Figure 2. Relationship between DC power and vehicle speed under varying load conditions (50-200 kg)

Figure 2. Presents the relationship between vehicle speed and the average efficiency of the PMSM-based drivetrain system. It can be observed that efficiency increases significantly with increasing speed, from 66.28% at 10 km/h to 90.77% at 40 km/h. The most pronounced improvement occurs within the low-to-medium speed range, indicating a reduction in the relative impact of constant losses such as switching losses and core losses on the total power. As the speed increases further, the rate of efficiency improvement gradually decreases, suggesting that the system approaches a saturation region. These results confirm that speed is a dominant parameter in enhancing the energy conversion performance of the PMSM-based system.

Table 1. Mean System Efficiency under Various Speed Conditions

Speed (km/h)	Mean Efficiency (%)
10	66.28
20	77.24
30	85.26
40	90.77

Figure 3 illustrates the simultaneous relationship between DC power and the efficiency of the PMSM system with respect to vehicle speed. It can be observed that the DC power increases significantly with increasing speed, from approximately 1200 W at 10 km/h to nearly 2400 W at 40 km/h. At the same time, system efficiency also improves from around 66% to more than 90%. This indicates that although power consumption increases, the system operates more efficiently at higher speeds. This phenomenon reflects an improvement in the energy conversion ratio and suggests that the PMSM system exhibits an optimal operating region at medium to high-speed ranges. Table 2 shows that the average DC power increases significantly with increasing vehicle speed. At a speed of 10 km/h, the required power is 1203 W, which then rises to 1437 W at 20 km/h, 1816 W at 30 km/h, and reaches 2407 W at 40 km/h.

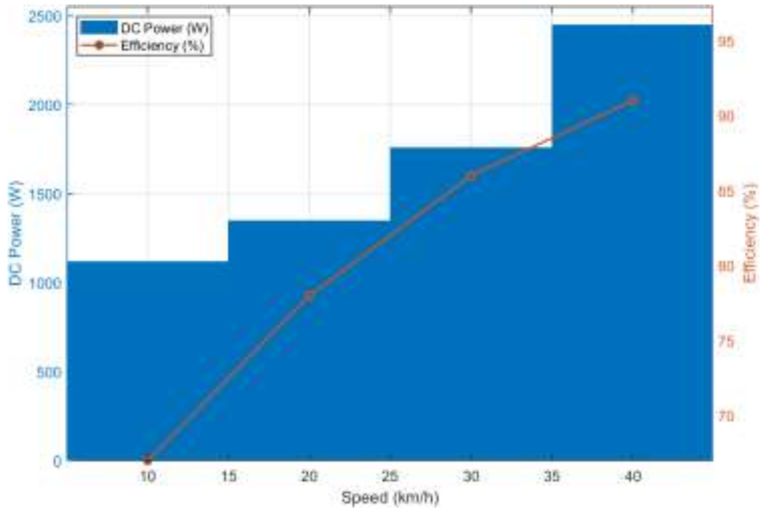

Figure. 3. Simultaneous Variation of DC Power and Efficiency with Increasing Vehicle Speed

This trend indicates that the energy demand of the PMSM drivetrain system is strongly influenced by operating speed, where an increase in speed leads to a non-linear rise in power consumption. This behavior is attributed to the increasing mechanical power requirements and system losses, resulting in higher energy consumption as vehicle performance improves.

Table 2. Mean DC Input Power under Various Speed Conditions

Speed (km/h)	Mean Power DC (W)
10	1203
20	1437
30	1816
40	2407

Table 3. Impact of Load Variation on System Efficiency

Load (kg)	Mean Efficiency (%)
50	79.65
100	80.25
150	79.23
200	80.38

Table 3 shows that load variation has a relatively minor effect on the average efficiency of the PMSM-based drivetrain system. The efficiency values remain within a narrow range, between 79.23% and 80.38%, despite the load increasing from 50 kg to 200 kg. This indicates that the PMSM system is capable of maintaining stable energy conversion performance under varying load conditions.

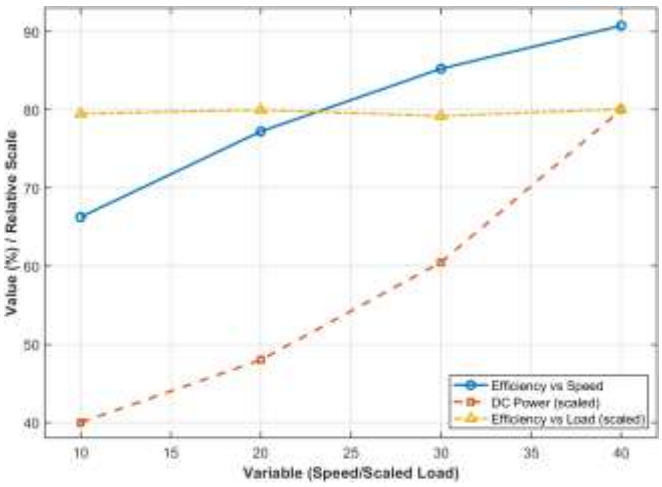

Fig. 4. Relationship of Efficiency and Power as Functions of Speed and Load

However, the slight fluctuations in efficiency may be attributed to changes in motor torque demand and current. Overall, these results confirm that speed is a more dominant factor than load in influencing the system efficiency. Fig. 4 presents a comparative relationship between efficiency with respect to speed, DC power, and efficiency with respect to load in an integrated graph. It can be observed that efficiency increases significantly with increasing speed, from approximately 66% to more than 90%, indicating the dominant influence of speed on system performance. Meanwhile, DC power also increases progressively, reflecting the growing energy demand at higher speeds. In contrast, efficiency with respect to load remains relatively stable within the range of 79–80%, indicating that load variation has a minimal impact on efficiency. These results confirm that speed is the primary factor in determining the performance of the PMSM-based system.

Table 5. Estimated Specific Energy Consumption under Various Operating Conditions

Speed (km/jam)	Energy (Wh/km)
10	118
20	71
30	61
40	60

Table 6. Accuracy Validation of Measurement Instruments

Parameter	Error (%)
AC Current	0.79
DC Current	0.63
AC Voltage	4.87
DC Voltage	0.07

Table 7. Synthesis of the Effects of Key Variables

Parameter	Effect of Speed	Effect of Load
Efficiency	Highly dominant	Weak
DC Power	Highly dominant	Moderate
DC Current	Dominant	Dominant
Energy per km	Dominant	Weak

Table 5 shows that the specific energy consumption decreases significantly with increasing vehicle speed, from 118 Wh/km at 10 km/h to approximately 60 Wh/km at 40 km/h. This indicates an improvement in energy utilization efficiency at higher speeds, where the effect of constant losses becomes relatively smaller compared to the total energy consumption. Table 6 demonstrates that the measurement system exhibits good accuracy, with errors below 1% for both DC current and voltage measurements, although the AC voltage measurement shows a higher error of 4.87%. Meanwhile, Table 7 confirms that speed is the dominant factor influencing both efficiency and power, whereas load has a more limited impact on system performance.

Table 8. PMSM System Efficiency as a Function of Vehicle Speed

Speed (km/jam)	Efficiency 50 kg (%)	Efficiency 100 kg (%)	Efficiency 150 kg (%)	Efficiency 200 kg (%)	Efficiency means (%)
10	68.2	65.9	64.8	66.2	66.28
20	76.5	77.8	76.9	77.5	77.24
30	84.3	86.1	84.7	86.0	85.26
40	89.6	91.2	90.5	91.8	90.77

Table 8 shows that the efficiency of the PMSM system increases consistently with increasing vehicle speed across all load variations. At a speed of 10 km/h, the efficiency ranges between 64.8% and 68.2%, and it increases to more than 90% at 40 km/h. The relatively uniform improvement pattern across all load conditions indicates that speed has a dominant influence on system efficiency. The differences in efficiency among various load levels are relatively small, suggesting that the system performance remains stable under load variations. The average efficiency also shows a significant increase, confirming that the PMSM system operates more optimally at medium to high-speed ranges.

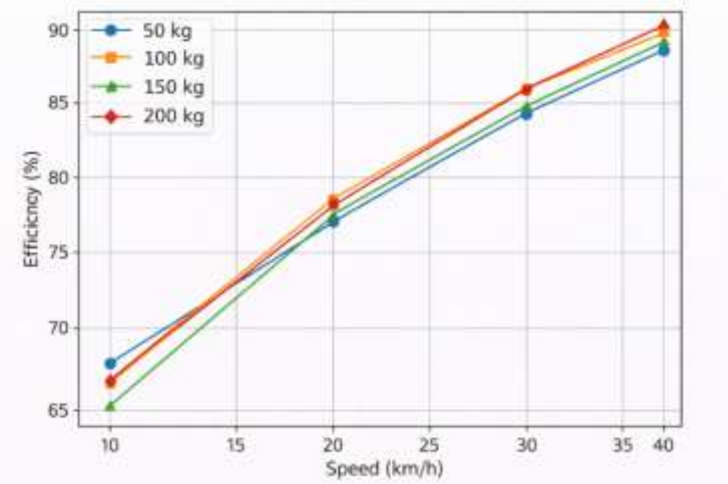

Figure 5. Variation of System Efficiency with Speed at Different Loads

Figure 5 illustrates the relationship between PMSM system efficiency and vehicle speed under various load conditions. It can be observed that efficiency increases consistently with increasing speed across all load levels, from approximately 65–68% at 10 km/h to more than 90% at 40 km/h. The nearly parallel trend of the curves indicates that the effect of load on efficiency is relatively small compared to the influence of speed. In addition, at higher speeds, the efficiency values across different loads tend to converge, suggesting stable system performance. These results confirm that the PMSM system operates more optimally at medium to high-speed ranges. Table 9 shows that the rate of efficiency improvement of the PMSM system tends to decrease as vehicle speed increases. The highest efficiency gain occurs in the 10–20 km/h interval, with an increase of 10.96%, followed by 8.02% in the 20–30 km/h interval, and further decreasing to 5.51% in the 30–40 km/h interval. This pattern indicates that the most significant performance improvement occurs at low to medium speeds. This observation is further supported by Table 10, where the efficiency gradient decreases from 1.10 to 0.55% per km/h. This trend suggests that the system begins to approach an efficiency saturation region at higher speeds.

Table 9. Incremental Efficiency Change as a Function of Speed

Speed Interval (km/jam)	increment Efficiency (%)
10 → 20	+10.96
20 → 30	+8.02
30 → 40	+5.51

Figure. 6 illustrates the relationship between PMSM system efficiency and vehicle speed based on experimental data and a linear regression approach. It can be observed that efficiency increases significantly from approximately 66% at 10 km/h to more than 90% at 40 km/h. The linear regression curve closely follows

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the trend of the experimental data, indicating a strong and nearly linear relationship between speed and efficiency

Table 10. Rate of Change of Efficiency per Unit Speed

Speed (km/jam)	Efficiency (%)	Gradien (Δη/Δv) (% per km/jam)
10–20	66.28 → 77.24	1.10
20–30	77.24 → 85.26	0.80
30–40	85.26 → 90.77	0.55

Although slight deviations are observed at lower and higher speeds, the regression model is still able to represent the overall system behavior effectively. These results confirm that speed is a dominant parameter in improving the efficiency performance of the PMSM-based system

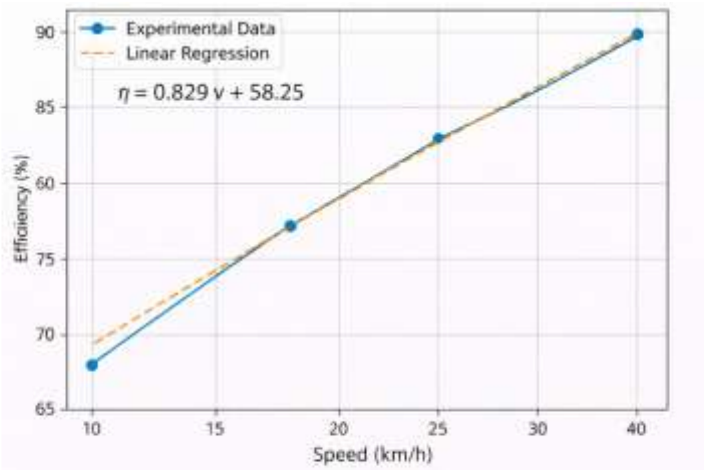

Figure. 6. Variation of System Efficiency with Respect to Speed.

4. CONCLUSION

Based on the study findings, the performance of the PMSM-based electric vehicle drivetrain is primarily influenced by operating speed. System efficiency increases from approximately 66% at 10 km/h to over 90% at 40 km/h, indicating that higher speeds improve energy conversion efficiency. In contrast, load variation has a relatively minor effect on efficiency, which remains approximately 79–80%, although increasing load results in higher current and power demand. Specific energy consumption decreases from 118 Wh/km to approximately 60 Wh/km as speed increases, demonstrating more efficient energy utilization. Efficiency-gradient analysis further shows diminishing efficiency gains at higher speeds, indicating that the drivetrain approaches an optimal operating region. Measurement validation yields an error below 5%, confirming the reliability and representativeness of the experimental data. Overall, the results demonstrate that medium-to-high-speed operation provides the most energy-efficient operating region for the PMSM-based drivetrain.

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