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THE SIGNIFICANCE OF CONVERTER LOSSES AND THE ROLE OF TRANSMISSION SYSTEMS IN THE OVERALL EFFICIENCY OF EV PROPULSION

M. Devika[1], M. Maheswaran[2], Bibin P Varghese[3], S. Selvam[4], Dr. P. Vijayakumar[5] and P.Chandrasekaran[6]
[1]Assistant Professor, Department of Electrical and Electronics Engineering, JCT College of Engineering and Technology, Coimbatore, India
[2]Professor, Department of Mechatronics Engineering, Nehru Institute of Engineering and Technology, Coimbatore, India
[3]Assistant Professor, Department of Mechanical Engineering, Providence College Of Engineering Chenganuur, Alappuzha, India
[4]Professor, Department of Mechanical Engineering, Aditya Institute of Technology Coimbatore, India
[5]Assistant Professor, Department of Aeronautical Engineering, Nehru Institute of Technology (Autonomous), India
[6]Associate Professor,Department of Mechanical Engineering, Dhanalakshmi Srinivasancollege of Engineering, Coimbatore, India
[1]devikav66@gmail.com

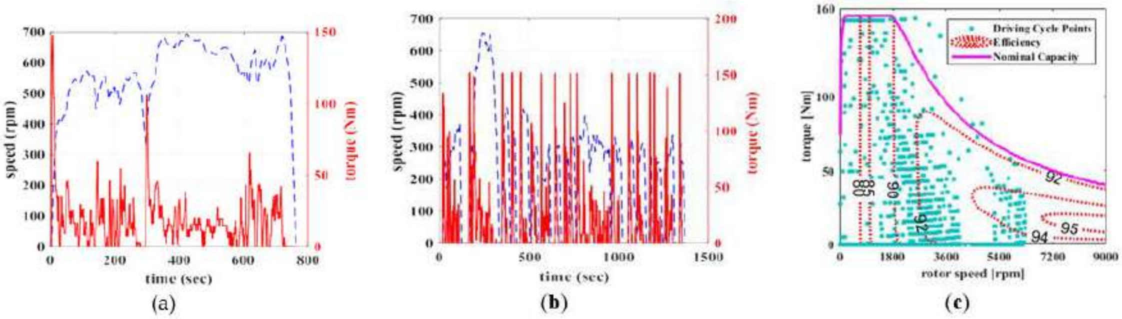
ABSTRACT

The increasing adoption of Electric Vehicles (EVs) as an eco-friendly alternative to traditional internal combustion engine vehicles has led to a growing focus on improving their propulsion system efficiency. This study investigates the significance of converter losses and the role of transmission systems in the overall efficiency of EV propulsion. The research begins by analyzing the various components involved in the EV propulsion system, with a particular emphasis on the power electronics converters. These converters play a crucial role in transforming electrical power between the battery pack and the electric motor. The impact of converter losses on the overall efficiency of the EV propulsion system is examined in detail, considering both AC-DC and DC-AC conversion stages. Furthermore, the study delves into the different types of power electronics topologies, such as pulse-width modulation (PWM) and resonant converters, evaluating their efficiency and suitability for EV propulsion applications. Techniques for minimizing converter losses, such as advanced switching strategies and the use of wide-bandgap semiconductors, are explored to enhance the overall efficiency of the propulsion system. Another key aspect investigated in this research is the role of transmission systems in EVs. While most early EVs adopted single-speed transmissions for simplicity, emerging advancements in transmission technologies have introduced multi-speed transmissions. The study examines the impact of transmission systems on EV propulsion efficiency, considering factors such as torque delivery, speed range, and powertrain losses. To quantify the effects of converter losses and transmission systems on the overall efficiency of EV propulsion, mathematical models and simulations are developed and validated. Real-world driving scenarios are analyzed to assess the performance of different power electronics configurations and transmission setups, providing insights into their practical applicability. Moreover, the study explores the potential for regenerative braking systems to recover energy during deceleration and its influence on the overall propulsion system efficiency. The integration of regenerative braking with the power electronics converters and transmission systems is investigated to optimize energy recovery and improve overall vehicle range. The outcomes of this research contribute to the understanding of how converter losses and transmission systems impact the efficiency of EV propulsion. The findings provide valuable guidance for designers and manufacturers to optimize power electronics and transmission configurations, leading to more energy-efficient and environmentally sustainable EVs.

IndexTerms–Electric Vehicles, converter losses, power electronics, transmission systems, propulsion efficiency, multi-speed transmission, regenerative braking, wide-bandgap semiconductors, efficiency optimization

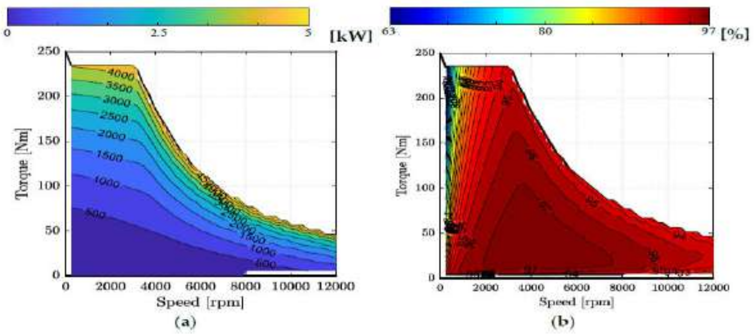
INTRODUCTION

The passage explores various aspects related to electric machine efficiency and losses in the context of electric and hybrid electric vehicles (EVs). It begins by discussing the efficiency criteria used to categorize motors in NEMA and IEC standards. Permanent magnet synchronous motors (PMSMs) are highlighted for their popularity in traction applications due to their high power density. However, research is ongoing to improve efficiency and reduce reliance on rare-earth magnet materials, with induction and synchronous reluctance motors being explored as alternatives. Efficiency maps (EMs) are introduced as contour plots used in machine design research to showcase the highest efficiency at different torque and speed levels. These maps are essential for calculating the overall energy consumption of the vehicle's propulsion system throughout a driving cycle. Accurate loss estimation in electric machines is identified as a critical factor in determining motor efficiency. The passage stresses the significance of understanding loss variation across a wide range of torque and speed for designing an optimal drivetrain system for EVs. It compares the efficiency maps of different motor types, highlighting internal permanent magnet synchronous motors (IPMSMs) for their superior efficiency compared to induction motors (IMs), particularly at lower speeds. Various types of losses, such as core losses and ohmic losses, are explained in relation to their impact on machine efficiency, which is influenced by voltage, current, speed, and torque. However, the passage acknowledges that some forms of losses have not been adequately investigated and modeled in existing literature, calling for more comprehensive research to understand their causes and fluctuations across different torque and speed levels. Overall, the passage provides valuable insights into the significance of efficiency maps and loss estimation in designing electric machine drivetrain systems for EVs. It encourages further research to address the existing gaps in knowledge and offers this content as a reference for those interested in optimizing electric machine efficiency for electric and hybrid vehicles.



(a) (b) (c)

Figure 1. Two driving cycles' torque-speed profiles that were used in several academic publications for optimisation investigations. Data for this graphic were gathered from [23]. Highway Fuel Economy Test (HWFET), Urban Dynamometer Driving Schedule (UDDS), Induction Motor Efficiency Counter, and Operating Points of the UDDS Driving Cycle in the Torque-Speed Envelope.



(a) (b)

Figure 2. The efficiency and loss maps of a sample 50 kW IPMSM that was operated at its highest level of efficiency at each operating point. The IPMSM under study is intended for EV use. The information for this plot was gathered from [20,24]. (A) An IPMSM's total loss map. (a) An IPMSM's efficiency map.

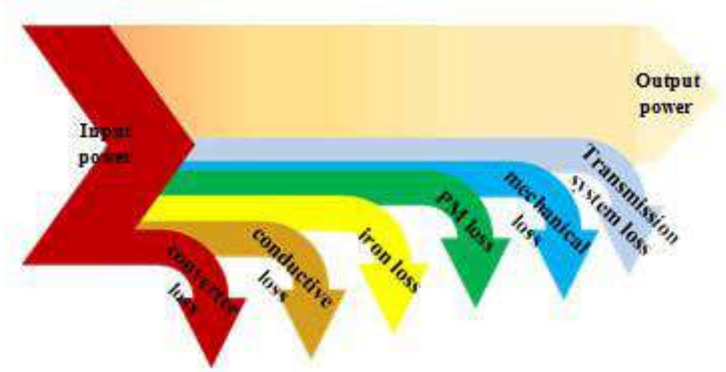


Figure 3. The various loss components of an electric machine used in propulsion system of EVs.

Section 2 of the paper presents a comprehensive calculation method for each type of loss occurring in different sections of the EV's drivetrain system. It elucidates how these losses vary under different torque and speed conditions and identifies the key factors influencing each loss component.In Section 3, the paper describes in detail the experimental extraction process for each loss component. The section outlines the procedures and methodologies used to measure and quantify the various types of losses across the drivetrain system. It highlights the importance of precise measurement devices and power analyzers in obtaining efficiency maps during experimental measurements, considering all categories of losses. Electric vehicle losses refer to the energy dissipation that occurs during the operation of an electric vehicle (EV). These losses occur in various components of the EV's propulsion system and can significantly impact the overall efficiency and range of the vehicle. The major types of losses in electric vehicles include:

1. **Ohmic Losses:** Also known as Joule losses, ohmic losses occur in the conductors (wires) of the electric motor and power electronics due to the resistance of the materials. When current flows through the conductors, it encounters resistance, leading to heat dissipation. Ohmic losses are proportional to the square of the current and can vary with torque and speed.

2. **Core Losses:** Core losses, also known as iron losses, occur in the magnetic core of the electric motor due to hysteresis and eddy currents. As the magnetic fields change during motor operation, energy is lost in the core material. Core losses are often dependent on the voltage and frequency of the power supply.

3. **Permanent Magnet (PM) Losses:** PM losses occur in permanent magnet motors due to the interaction of the magnetic fields with the magnets. These losses can be related to eddy currents induced in the magnets, leading to heating and energy dissipation.
4. **Converter Losses:** The power electronics converters used in EVs, such as inverters and DC-DC converters, have their own losses due to switching devices (like transistors), conduction losses, and other inefficiencies. These losses can vary with the type and design of the converter.

5. **Mechanical Losses:** Mechanical losses in the drivetrain system of an EV include friction losses in bearings, gears, and other mechanical components. These losses occur when the mechanical parts move and rub against each other, leading to energy dissipation.

6. **Windage and Stray Losses:** Windage losses occur due to air resistance faced by the rotating components of the electric motor. Stray losses refer to losses in other parts of the motor that are not directly related to the core or winding losses.

7. **Transmission Losses:** Transmission losses refer to energy losses that occur when transferring power from the electric motor to the wheels through the transmission system. These losses are influenced by the type of transmission (e.g., gearbox) and its efficiency.

Reducing these losses is crucial for improving the overall efficiency and range of electric vehicles. Efficient design and material selection, advanced power electronics, improved cooling systems, and optimization of control algorithms are some of the ways to minimize these losses and enhance the performance of electric vehicles.

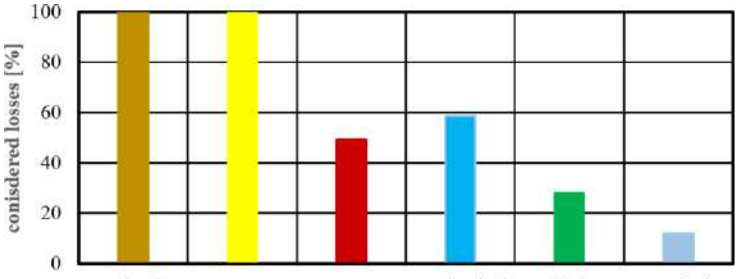
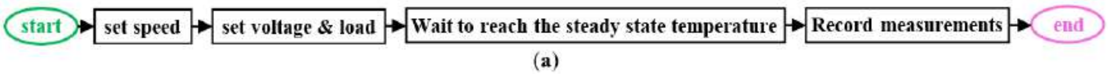


Figure 4. The statistic of documented research focused on the impact of various types of losses on EM of electrical machines during the last three decades (1992 to 2021).

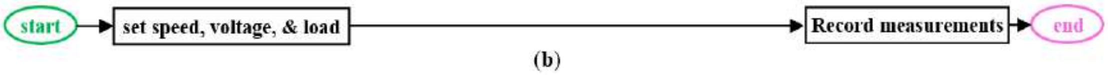
EXPERIMENTAL SETUP FOR MEASUREMENT OF THE LOSSES

The experimental calculation of losses is conducted following the efficiency extraction standards set by IEEE and IEC (i.e., IEEE 1812, IEC60034-2-1-2A, IEEE 112, and IEC 60034-2-1-1B [90]). The flowchart representing the process of calculating motor efficiency based on these methods is depicted in Figure 12. In these standardized procedures, the speed and load conditions are adjusted to ensure that the machine operates at its rated temperature.In summary, the efficiency of the motor is determined through experimental calculations using well-established IEEE and IEC standards. These standardized methods ensure accurate and reliable measurement of losses, and the flowchart in Figure 5 outlines the step-by-step process for calculating motor efficiency based on these procedures. By carefully controlling the speed and load conditions to maintain the motor at its rated temperature, researchers can obtain precise efficiency values for the electric machine.

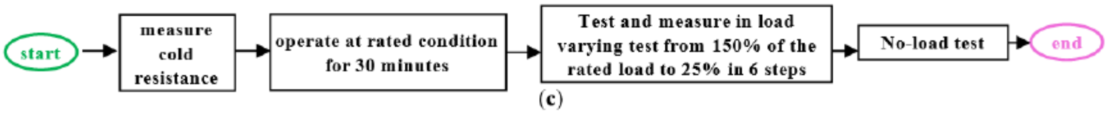
IEEE1812PMSMLoadTest



IEC60034-2-1 Method2-1-2APMSMandDC motorsInput/Output



IEEE112MethodAandBIM



IEC60034-2-1Method2-1-1BIM

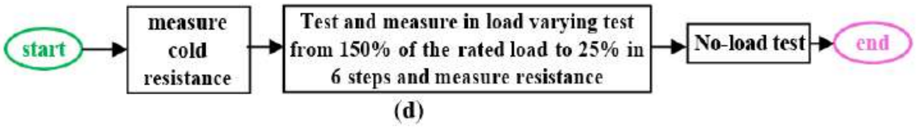


Figure 5. The conventional methods for the extraction of the motor's efficiency experimentally based on IEEE and IEC standards.(**a**) the procedure of the calculation of the efficiency at a certain load and speed for PMS motors based on IEEE standard.(**b**) the procedure of the calculation of the efficiency at a certain load and speed for PMS and DC motors based on IEC standard.(**c**) the procedure of the calculation of the efficiency at a certain

load and speed for the induction motors based on IEEE standard.(**d**) the procedure of the calculation of the efficiency at a certain load and speed for the induction motors based on IEC standard.

To accurately calculate the efficiency of an electric machine, standard methods involve setting up an experimental setup to measure both the input and output power of the machine. By subtracting the output power from the input power, the losses occurring within the machine can be determined, leading to an accurate assessment of its efficiency. Similarly, to assess the efficiency and losses of each component in an electric vehicle (EV) drive system, it is crucial to strategically place measuring devices within the system.

Figure 6 illustrates the complete drivetrain system of an EV, along with the monitoring and measuring devices required for experimental loss separation in different parts of the system. These measuring devices play a vital role in accurately quantifying the losses in individual components, including the electric machine, power converter, transmission system, and other relevant parts.

By analyzing the input and output power data obtained from these measuring devices, researchers can determine the efficiency of the electric machine and identify the losses associated with it. The same approach can be applied to the other components of the EV drive system, providing valuable insights into the overall performance and efficiency of the entire system.

In summary, conducting experimental loss separation in an EV drive system necessitates the strategic placement of measuring devices and the collection of input and output power data. This method enables researchers to accurately evaluate the efficiency and losses of each component, contributing to the optimization and improvement of electric vehicle technology.

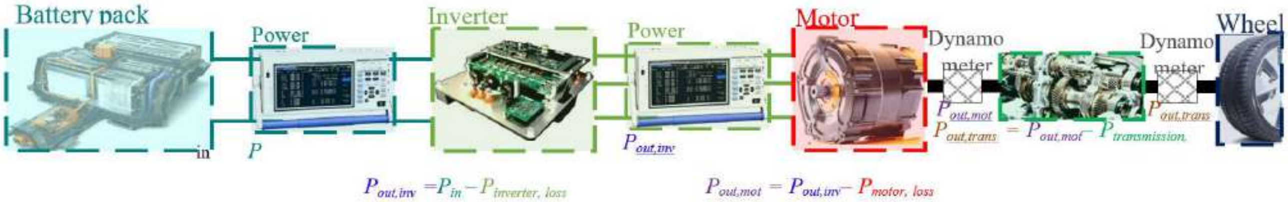


Figure 6. The placement of power analyzers and dynamo meters to measure each loss component of the EV propul- sion system.

PM Losses for Permanent Magnet Motors

PM losses are a significant component of the overall losses in PM machines. An indirect technique can be used to measure these losses, involving the extraction of core loss, mechanical loss, and ohmic losses of the machine. By subtracting the total input power at loading conditions from the summation of total output power and measured losses, the PM losses can be determined.For a more accurate estimation of PM losses using the indirect measurement technique, it is crucial to collect the ohmic losses of the stator when the rotor is removed from the stator. This step ensures that the ohmic losses attributed to the stator are correctly accounted for in the calculation.However, it is important to note that the indirect method may not be entirely precise because it could potentially include some portion of stray losses in the PM loss estimation. Stray losses occur due to magnetic field leakage and other factors not accounted for in the direct measurements of core, mechanical, and ohmic losses.Moreover, the amplitude and frequency of the induced eddy currents on the PMs directly impact the PM temperature. In a study [166], researchers measured the temperature of the PM parts and used Equation (1) to estimate the PM losses.In summary, PM losses in PM machines can be indirectly measured by subtracting the total output power and measured losses from the total input power at loading conditions. While this method provides a reasonable estimation, it may not be entirely accurate due to the potential inclusion of stray losses. Nonetheless, efforts can be made to enhance accuracy, such as conducting measurements of stator ohmic losses with the rotor removed. Additionally, accounting for the impact of induced eddy currents on PM temperature can further improve the estimation of PM losses.

$$P_{PM} = \rho \times c \times N_{PM} \times V_{PM} \times \frac{\Delta\theta}{\Delta t} \tag{1}$$

In this equation, the specific mass density (ρ) and heat capacity (c) of the PMs are vital parameters. Additionally, the number of PM elements (NPM) and the volume of a single PM part (VPM) are included in the equation. The rate of temperature variation (ΔT/Δt) is a crucial factor obtained directly from the measured temperature variation curve. Together, these parameters enable a comprehensive estimation of the PM losses in the system.In summary, the equation takes into account essential parameters such as mass density, heat capacity of the PMs, number of PM elements, and the volume of a single PM part. The rate of temperature change (ΔT/Δt), derived from the temperature variation curve, plays a key role in accurately estimating the PM losses in the system.

Transmission System Losses

The transmission system losses represent the final component of losses in the propulsion system of an electric vehicle (EV). These losses can be determined by subtracting the mechanical input power to the transmission system from its mechanical output power.Creating an efficiency map (EM) for electric machines requires a high level of accuracy, which is achieved by plotting between 300 to 1600 data points [167,168]. However, calculating the efficiency map involves sweeping through different pairs of d- and q-axes currents to find the minimum loss point for each set of torque and speed. As a result, conducting loss separation over a driving cycle can be a time-consuming process, as obtaining an accurate loss map for each component requires considering the mentioned details for at least 300 operating points across the driving cycle.In summary, accurately determining efficiency maps for electric machines necessitates a substantial number of data points, and the efficiency map calculation for loss separation in a driving cycle can be time-consuming. Nonetheless, it is crucial to consider a sufficient number of operating points to ensure a comprehensive understanding of losses and overall efficiency in the EV drivetrain system. This comprehensive approach is vital for optimizing the performance and efficiency of the electric vehicle drivetrain.

DC-DC converter losses refer to the energy dissipation that occurs in the DC-DC converter during its operation. A DC-DC converter is an electronic device used to convert one DC voltage level to another. It plays a crucial role in electric vehicles (EVs) as it allows for efficient power transfer between different voltage sources, such as the battery pack and various electrical systems in the vehicle.

The major types of losses in a DC-DC converter include:

1. **Switching Losses:** Switching losses occur when the semiconductor switches (e.g., MOSFETs or IGBTs) in the DC-DC converter turn on and off to regulate the output voltage. During switching, there is a brief period when both the voltage and current are non-zero, leading to energy dissipation. These losses are proportional to the switching frequency and can be reduced by using high-performance switching devices and optimized control strategies.

2. **Conduction Losses:** Conduction losses occur due to the finite resistance of the semiconductor switches and the conducting elements (e.g., inductor and capacitor) in the converter circuit. When the switches are in their conducting state, there is a voltage drop across them, resulting in power dissipation. These losses can be minimized by selecting components with low resistance and optimizing the conduction path.

3. **Diode Losses:** Some DC-DC converters use diodes as part of their circuitry. Diode losses occur due to voltage drop across the diodes when they are forward-biased during the conduction phase. Similar to conduction losses, diode losses can be minimized by using low-resistance diodes.

4. **Inductor Losses:** Inductor losses, also known as core losses, occur in the inductor used in the converter circuit. These losses are caused by hysteresis and eddy currents in the inductor's magnetic core material as the

current changes. Choosing high-quality magnetic materials and minimizing core losses can help reduce this type of loss.

5. **Capacitor Losses:** Capacitor losses occur in the output and input capacitors of the DC-DC converter. These losses are mainly due to dielectric losses and equivalent series resistance (ESR) of the capacitors. Using capacitors with low ESR and high-quality dielectric materials can help minimize these losses.

6. **Control and Gate Drive Losses:** Control circuitry and gate drive circuits in the DC-DC converter consume some power to operate. These losses are generally small compared to other losses in the converter but can be reduced through efficient control algorithms and low-power gate drivers.

Efficient design and operation of the DC-DC converter are essential to minimize these losses and improve overall system efficiency. Advanced semiconductor technologies, optimized component selection, and sophisticated control strategies are employed to achieve higher efficiency in modern DC-DC converters used in electric vehicles.

RESEARCH GAPS AND FUTURE OPPORTUNITIES

The transmission system losses constitute the final component of losses in the propulsion system of an electric vehicle (EV). As shown in Figure 13, these losses can be determined by subtracting the mechanical input power to the transmission system from its mechanical output power.Creating an efficiency map (EM) for electric machines demands a high level of accuracy, achieved by plotting between 300 to 1600 data points [167, 168]. However, calculating the efficiency map involves sweeping through different pairs of d- and q-axes currents to find the minimum loss point for each set of torque and speed. Consequently, conducting loss separation over a driving cycle can be a time-consuming process, as obtaining an accurate loss map for each component requires considering the mentioned details for at least 300 operating points across the driving cycle.

In conclusion, accurately determining efficiency maps for electric machines requires a significant number of data points, and the efficiency map calculation for loss separation in a driving cycle can be time-consuming. However, it is crucial to consider a sufficient number of operating points to ensure a comprehensive understanding of losses and overall efficiency in the EV drivetrain system. This comprehensive approach is essential for optimizing the performance and efficiency of the electric vehicle drivetrain.

CONCLUSION

This paper underscores the utmost importance of accurately predicting losses to design electric machines that can achieve maximum efficiency. Designing machines for optimal operation over a driving cycle presents additional challenges due to the varying losses at different operating points and supply factors. The review delves into the dependency of each loss component on the efficiency of electric machines at different operating regions. It comprehensively explains methods for measuring and calculating machine losses, highlighting the variations in loss among different electric machines and showcasing their respective strengths and weaknesses for operation over a wide torque-speed range.Beyond electric machines, power converters also play a crucial role in the drivetrain system of electric vehicles. The paper discusses the significance of converter losses and their impact on the overall efficiency of EV propulsion systems, particularly at higher speeds. Furthermore, the review briefly covers transmission systems in EVs, discussing their specifications in terms of loss and efficiency. Proper selection of the transmission system is shown to be of utmost importance based on the findings from the literature review.Overall, the paper emphasizes that designing an optimal propulsion system for EVs necessitates careful consideration of various factors. While electric machines offer high efficiency at higher speeds, the efficiency of power converters and transmission systems tends to decrease as speed increases. Therefore, a comprehensive investigation of the performance of all sections of an EV propulsion system is essential during the design process.The research gaps identified through the literature review are highlighted, and potential future research subjects in loss analysis of electric machines are presented. The paper also explains how computational intelligence models can aid in loss prediction for electric machines.In conclusion, the paper underscores the critical role of accurately predicting losses in designing efficient electric machines for electric vehicles. It provides valuable insights into the complexities of loss analysis and identifies areas for further research and development to optimize the performance of EV propulsion systems.

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