A Future Review and Reliability Evaluation of PMSM in EV

Hammoude K. Bachache
Department of Electrical Engineering-Islamic Azad University Isfahan- Iran
tech-2006@yahoo.com

Ramtin Sadeghi*
Islamic Azad University-Isfahan- Iran
ramtinsadeghui@yahoo.com

Nasseer K. Bachache
Ministry of Higher Education
nasseer.kassim@gmail.com

Abstract :

In recent years, electric motors have advanced to meet the demands for improved efficiency, reliability, and sustainability. These motors enhance the driving experience by boosting torque, acceleration, and overall performance. As vehicle power output rises, there is increasing focus on cost, efficiency, and driving dynamics. This paper examines the reliability of motors used in EVs and their drives. It thoroughly reviews relevant research, incorporating findings from various studies on dynamic reliability, fault tolerance, and thermal effects. The engineering strategies and comparative insights provided here offer a practical guide for future research and development in EV motor drive reliability. This article delivers a comprehensive review of the comparative reliability of PMSMs compared to other EV motor drives, highlighting their performance in dynamic conditions, design challenges, and fault-tolerant features.

Keywords: Electric Vehicle (EV) PMSM , BLDC ,SRM ,Induction Motor IM ,Reliability .

مراجعة تقييم موثوقية الماطور التزامني ثابت المغناطيسي في السيارات الكهربائية مع النظرة المستقبلية

حمودي قاسم باججي
جامعة ازاد الاسلامية – قسم هندسة الكهرباء

رامتين صادقي
جامعة ازاد الاسلامية

نصير قاسم باججي
جامعة مدينة العلم

الخلاصة :

في السنوات الأخيرة، تطورت المحركات الكهربائية لتلبية متطلبات السيارات الكهربائية من خلال تحسين الكفاءة والموثوقية والاستدامة. مع ازدياد إنتاج السيارات الكهربائية يلاحظ يزداد التركيز على التكلفة والكفاءة وديناميكيات القيادة. لذلك يجب ان يضمن تصميم المحركات الكهربائية وأجهزة السيطرة عليها تُحسّن القيادة من خلال تعزيز عزم الدوران والتسارع والأداء العام. تتناول هذه الورقة البحثية موثوقية المحركات المستخدمة في السيارات الكهربائية ومحركاتها. وتستعرض بدقة الأبحاث ذات الصلة، تتضمن النتائج المستندة الى عدة دراسات حول الموثوقية الديناميكية، وتحمل الأعطال، والتأثيرات الحرارية. تُقدم الاستراتيجيات الهندسية والرؤى المقارنة المُقدمة هنا دليلاً عمليًا للبحث والتطوير المستقبلي في مجال موثوقية محرك السيارات الكهربائية. اثبتت هذه المقالة وبعد مراجعة شاملة للموثوقية المقارنة ان المحرك من نوع الماطور التزامني ذو المغناطيس الثابت PMSM كان الأكثر ملائمة لمتطلبات السيارات الكهربائية مقارنةً بأنظمة محركات الأخرى، مُسلّطةً الضوء على أدائها في الظروف الديناميكية، وتحديات التصميم، وميزات تحمل الأعطال. في حين ان الماطور الحثي IM الأكثر موثوقية على كل المحركات .

الكلمات المفتاحية : المركبات الكهربائية EV، PMSM، BLDC ، SRM، محرك الحث IM، الموثوقية.

* Corresponding author : Ramtin Sadeghi .

1. Introduction

Demand for electric motors (e-motors) is steadily rising as legislation worldwide encourages the adoption of low- and zero-emission vehicles that rely on electrified powertrains [2]. Global light-duty vehicle (LDV) and EV production, including battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and hybrid vehicles, [3] is forecasted to exceed 70 million units by 2030 [5]. EVs have become a crucial solution for reducing carbon emissions and enhancing energy efficiency in modern transportation [5]. The electric motor drive system is vital for EV performance and reliability [6]. Among various motors used in EVs, the permanent magnet synchronous motor (PMSM) has gained notable attention due to its high efficiency [7], smooth torque, and excellent power density [8]. However, the EV motor technology landscape also includes brushless DC (BLDC) motors [9], switched reluctance motors (SRMs) [10], and induction motors (IMs) [11], each with unique benefits and challenges [12]. Understanding these factors is essential for engineers and designers seeking to optimize EV powertrains for increased durability and efficiency [13]. The analysis references multiple studies examining the effects of dynamic loads [14], wear mechanisms, thermal effects, and advanced control techniques on motor reliability [15].

2. Overview of Electric Vehicle Motor Technologies

Electric vehicle motor technologies have developed over the years, aiming to meet the challenges of operating conditions [16], efficiency requirements, and cost limitations. The primary types of motors used in EV applications include:

• Permanent Magnet Synchronous Motor (PMSM) [18]:

PMSMs use permanent magnets on the rotor to generate a constant magnetic field [18]. They deliver smooth torque, have high efficiency, and are frequently chosen for EV drivetrains due to their favorable power-to-weight ratio [19].

• Brushless DC Motor (BLDC) [20]:

BLDC motors operate using a rotor with permanent magnets and stator windings arranged in a trapezoidal layout [21], which produces a trapezoidal back electromotive force (EMF) [22]. They are valued for high-speed operation and simplified control mechanisms [23] but may yield higher torque ripple compared to PMSMs [24].

• Switched Reluctance Motor (SRM) [25]:

SRMs are characterized by their simple construction and robust design [26]; however, they tend to suffer from significant torque ripple and acoustic noise issues [27]. Recent advancements in design optimization and control strategies have aimed to mitigate these shortcomings [28].

• Induction Motor (IM) [29]:

Induction motors have long been used in industrial applications due to their durability and low maintenance requirements [30]. In the electric vehicle (EV) sector, they are valued for their cost-effectiveness and dependability across various driving cycles [30], although achieving high efficiency remains a challenge compared to PMSMs [31].

3. Reliability Fundamentals for EV Motor Drives

Reliability in EV motor drives depends on various factors, including dynamic loads, wear mechanisms, thermal stress, and electrical faults [32]. Understanding these reliability fundamentals is essential for optimizing motor designs to ensure safe and durable operation [33]. The following key aspects are critical for evaluating EV motor reliability:

3.1. Dynamic Loads and Mechanical Wear:

Under normal operation, EV motors encounter different load conditions that induce dynamic stress on motor components [34]. For PMSMs, the interaction between the permanent magnet parts and the stator windings leads to wear that can develop into failure modes over time [35]. Statistical techniques like climate forecasting and nonlinear damage theory are essential for predicting fatigue and failure caused by wear [36].

3.2. Thermal Management [37]:

Temperature is a crucial factor influencing the performance and reliability of all EV motors [38]. Particularly for PMSMs, high temperatures can damage winding insulation, demagnetize permanent magnets [39], and even harm semiconductor parts like IGBTs [40]. The way temperature affects these components has been widely studied, with test results highlighting the essential role of thermal regulation in prolonging motor lifespan.

3.3. Fault Correlation and Redundancy [41]:

Motor systems benefit from fault-tolerant designs, which include redundancy and control strategies that ensure continuous operation during faults [42]. Multi-phase and dual-winding configurations are increasingly used in PMSMs to enhance fault tolerance [43]. By employing vector space decomposition (VSD) and advanced current control methods, researchers have shown that PMSM drives can maintain stable performance despite open-circuit faults or other anomalies [44].

3.4. Control Strategies and Digital Signal Processing [45, 46]:

Advanced control systems are vital for monitoring motor performance and proactively addressing reliability issues [47]. Techniques such as finite element simulations and digital signal processing (DSP) help reduce torque ripple, improve fault diagnosis, and facilitate real-time adjustments in current profiles [48]. These reliability fundamentals form the basis for a more detailed comparison, enabling the evaluation of different motor types based on their dynamic performance, fault-tolerance features, and long-term durability of motor systems [49].

4. Comparative analysis of PMSM with Other motors

Engineers and researchers have conducted several comparative studies to assess the performance and reliability of PMSM in relation to BLDC, SRM, IM, and induction motors [50]. These analyses focus on multiple evaluation criteria, including torque ripple, efficiency, design complexity, cost, and fault tolerance [51]. The following subsections describe these comparisons.

4.1 Performance Characteristics

As mentioned earlier, PMSMs are known for their high efficiency and smooth torque output [18], which are vital for applications that require precision and consistency. In contrast, BLDC motors [20], although efficient and capable of high-speed rotation, typically exhibit a trapezoidal back EMF that can cause noticeable torque ripples under load. SRMs [25], on the other hand, face issues such as increased torque pulsations and acoustic noise, which can sometimes affect overall system reliability.

Table 1 summarizes the strengths and weaknesses of each motor type under typical operating conditions. The PMSM excels in efficiency and smooth operation, which directly contributes to increased reliability, while IM is the most robust in fault tolerance and economical with good performance, but it’s the lowest efficiency reliability. PMSMs often have complex rotor designs with permanent magnets and require precise positioning and balancing to ensure consistent performance [19]. The

Table (1) : Comparative Performance Analysis of EV Motors

Motor Type	**Torque Ripple**	**Efficiency**	**Fault Tolerance**	**Reliability Factors**
PMSM	Low	High	Advanced	High, with emphasis on thermal and wear management
BLDC	Moderate	Moderate	Simple	Efficient at high speeds but may require careful control to reduce ripple
SRM	High	Variable	High	Prone to noise and vibration; needs optimization to reduce pulsation effects
Induction Motor	Moderate	Moderate	Robust	Economics with good performance over diverse cycles, but lower peak efficiency

4.2 Design Complexity and Manufacturing Considerations

The complexity of motor design greatly affects their cost, manufacturability, and complexity involved in control and optimization strategies, such as those used in six-phase designs or dual-winding structures, emphasizes the need for advanced manufacturing and quality assurance processes.

In comparison, BLDC motors have a simpler structure due to the lack of brushes and the back EMF design [22], which simplifies control but may introduce other challenges related to dynamic performance. SRMs [28], although durable, typically need additional control algorithms to minimize their inherent torque pulsations.

4.3 Fault Tolerance and Operational Reliability

Fault tolerance is a crucial property for EV motors [32], as maintaining performance during fault conditions significantly impacts vehicle safety and reliability. Research on fault-tolerant strategies indicates that PMSMs benefit from techniques like phase angle adjustments and redundant winding configurations. For example, six-phase PMSMs have demonstrated notable reductions in torque ripple and improved fault tolerance by dynamically adjusting current profiles and employing Full Range Minimum Loss (FRML) strategies.

Dual-winding PMSMs are shown in Figure 1. They have several advantages, especially in maintaining a consistent magnetic motive force even under open-circuit conditions, by employing both hysteresis current control and normal decoupling transformations [40]. These strategies ensure that the remaining phases can compensate for a failed circuit, thereby sustaining operation until corrective actions are taken.

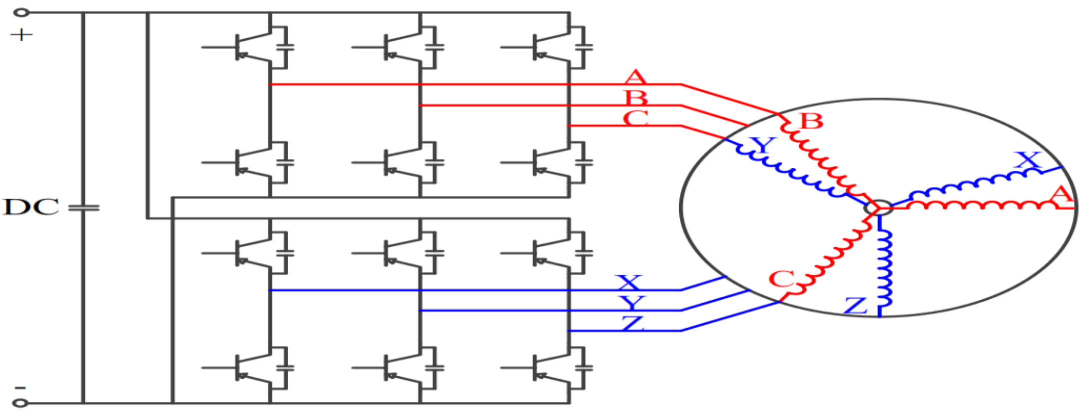

Figure (1) : The structure of dual three-phase PMSM drive.

In contrast, while BLDC and SRM drives may also include fault-tolerant features, their simpler design, especially in BLDC motors, often results in fewer built-in redundancies, which could cause more noticeable performance issues during faults. Induction motors are generally durable under fault conditions due to their sturdy construction, but they may not reach the same efficiency levels in dynamic scenarios as PMSMs.

4.4 Evaluate reliability parameters for PMSM in EVs

After evaluating the sources, we found that selecting reliable, comprehensive, and current information about the reliability of PMSMs in electric vehicles is essential for this research. The chosen fonts offer insightful analyses and technical details relevant to my study on comparing the reliability of PMSMs with other motor types. The webpages selected were chosen because they provide detailed, pertinent information on PMSMs and their reliability in electric vehicles, making them valuable for comparison. They come from reputable and up-to-date sources, ensuring high quality for this research. But other fonts did not focus specifically on reliability comparison or lacked comprehensive analyses. Some fonts were too broad or focused on technical details that did not directly contribute to understanding reliability parameters in the context of PMSMs and other motor drives.

5. Fault Tolerance and Design Considerations

The ongoing development of fault-tolerant techniques is essential for improving the reliability of EV motor drives. This section examines specific design methods and control strategies developed to enhance fault tolerance in PMSMs and compares these with solutions used in other motor drives.

5.1 Fault-Tolerant Control Strategies in PMSMs

Several studies have demonstrated the practical implementation of fault-tolerant control strategies in PMSMs. These strategies include:

- Vector Space Decomposition (VSD):

VSD coordinate transformation is employed to separate the motor windings into multiple subspaces, facilitating easier analysis and fault detection. This method supports a dual closed-loop control system that ensures motor performance even during faults.

- Dual-Winding Configurations:

Dual-winding PMSMs are specially designed to maintain performance even if one phase fails. Hysteresis current control and standard decoupling techniques have been experimentally validated to either decrease stator copper loss or boost torque output under fault conditions.

- Full Range Minimum Loss (FRML) Strategy:

This strategy combines maximum torque with minimum loss techniques to optimize current distribution. It ensures a balanced trade-off between torque output and reducing power loss during fault or degraded operating conditions.

5.2 Fault Tolerance in Other Motor Technologies

- BLDC Motors:

BLDC motors typically use simpler control methods. While they perform well during normal operation, their lower redundancy can lead to sudden performance drops in faulty conditions. However, their straightforward control often makes it easier to add external fault-tolerant systems when combined with additional electronic monitoring.

- Switched Reluctance Motors (SRMs):

SRMs inherently provide a high level of fault tolerance because of their simple structure and sturdy mechanical design. However, their vulnerability to excessive torque ripples and vibration can reduce overall reliability. Researchers are actively exploring adaptive control methods to solve these problems.

- Induction Motors:

Induction motors (IMs) are known for their sturdy construction and affordability. Their relatively simple design allows them to operate effectively under different conditions. However, in applications where high efficiency and dynamic performance are essential, such as in EV drivetrains, induction motors may be less reliable than PMSMs in extreme operating conditions.

5.3 Visualization: Fault-Tolerance Process Flow in PMSMs

Figure 2 is a flowchart diagram that outlines the fault-tolerance process flow used in PMSM systems. This diagram shows how PMSM systems respond to faults by employing advanced control strategies to maintain operational stability and protect critical components. Figure 3 presents the outline of the fault process in PMSM Systems.

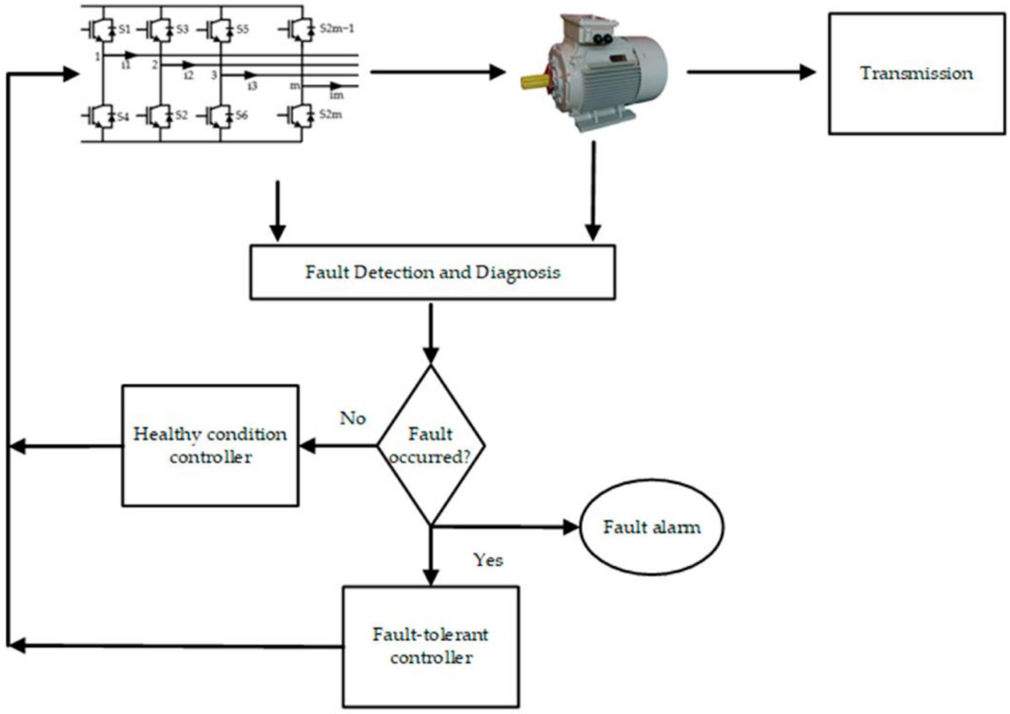

Figure (2): flowchart diagram of the fault-tolerance in PMSM systems:

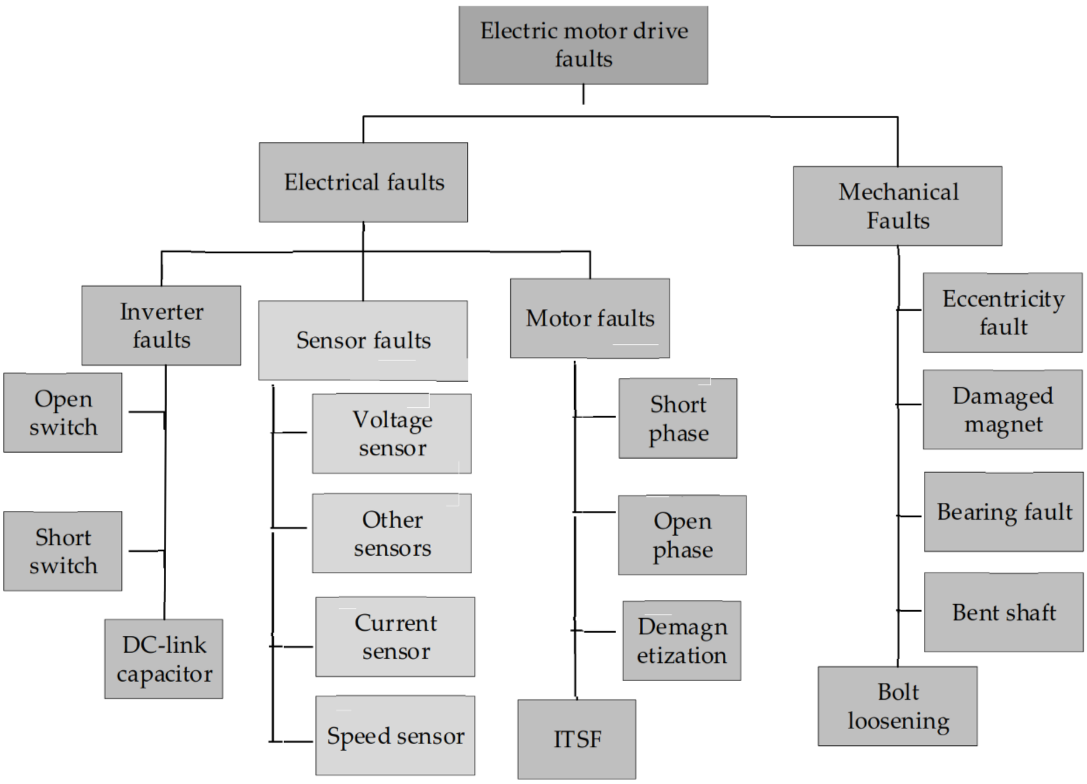

Figure (3): the outline of the Fault Process in PMSM Systems

6. Thermal and Dynamic Reliability Influences

Thermal and dynamic factors are essential in determining the reliability of EV motor drives. This section explores how temperature, dynamic loads, and system wear impact motor reliability and discusses design measures to counter these effects.

6.1 Thermal Effects on Motor Components

Temperature management is arguably the most vital factor for ensuring long-term reliability in EV motors, especially for PMSMs. Elevated operating temperatures can negatively impact several key components:

• Winding Insulation Degradation:
Higher operating temperatures accelerate the deterioration of insulation materials used in the stator windings, which can eventually lead to electrical faults or short circuits.

• Permanent Magnet Demagnetization:
High temperatures are known to weaken the magnetic strength of permanent magnets, resulting in decreased torque output and reduced overall efficiency. This demagnetization effect not only affects performance but also leads to early system failure.

• Semiconductor and IGBT Failures:
Power electronics shown in Figures 1 and 2, such as insulated gate bipolar transistors such as (IGBTs), are highly sensitive to temperature changes. Overheating can reduce their lifespan and affect their performance even under normal load conditions.

6.2 Dynamic Loading and Wear Mechanisms

Beyond thermal influences, dynamic loads from acceleration, deceleration, and changing road conditions generate cyclic stress in the motor structure. Researchers have applied advanced statistical methods to analyze fatigue loads on gears and motor components. Furthermore, nonlinear damage theories are used to understand how cyclic stress gradually causes material degradation. Incorporating wear characteristics into reliability models for PMSMs involves capturing the complex interactions between mechanical wear, dynamic load fluctuations, and strength degradation over time. This comprehensive approach ensures that reliability assessments are not only based on static design parameters but also consider the operational realities of dynamic loading.

6.3 Visualization: Comparative Thermal Effects on EV Motor Components

Table 2 summarizes the primary thermal and dynamic factors affecting various EV motor components and their impact on overall reliability. The clear summary of Table 2 shows how key components are affected by temperature and dynamic loads, emphasizing the need for effective thermal management and flexible design strategies.

Table (2) : Thermal and Dynamic Effects on EV Motor Components.

Component	Temperature Effect	Dynamic Load Influence	Reliability Impact
Winding Insulation	Accelerated aging and breakdown at high temperatures	Fatigue under cyclic loading	Reduced lifespan, electrical faults
Permanent Magnets	Demagnetization and reduced flux intensity	Vibrational forces affecting alignment	Lower torque output and efficiency
Bearings	Increased wear due to friction and heat buildup	Torque-induced stress	Increased maintenance and replacement needs
Power Electronics (IGBTs)	Thermal overload leading to reduced performance	Current fluctuations	Potential for catastrophic failure

7. Engineering Strategies for Enhancing PMSM Reliability

To address the challenges identified in previous sections, various engineering strategies have been developed to enhance the reliability of PMSMs in EV applications. These strategies include advanced design techniques, optimized control methodologies, and innovative material selections.

7.1 Advanced Cooling Techniques

Given the sensitivity of PMSMs to thermal effects, advanced cooling and thermal management solutions are essential. Engineers employ methods such as:

- Liquid Cooling Systems:

Using liquid coolants to absorb and dissipate heat from both the stator windings and the power electronic components, such as transistors and IGBTs, helps maintain a consistent temperature across the motor parts and reduces hotspots that can lead to failure.

- Enhanced Airflow Designs:

Optimized fan layouts and heat sinks ensure effective airflow over critical components, helping to manage temperatures even under heavy loads.

7.2 Material and Structural Optimizations

Improving the inherent reliability of PMSMs also requires selecting materials and structural designs that can withstand high temperatures and dynamic stress:

- High-Temperature Insulation Materials:

Using advanced polymers and insulation materials that can withstand higher thermal loads without degrading is essential for extending motor lifespan.

- Optimized Rotor and Stator Designs:

By using high-quality permanent magnets and durable structural materials, designers can ensure that both the rotor and stator undergo less wear and maintain their performance over time.

- Finite Element Analysis (FEA):

FEA programs, like ANSYS, are used during the design phase to simulate thermal and mechanical stresses, helping identify potential failure points before manufacturing. This method assists in refining design details and ensures the motor can withstand real operating conditions.

7.3 Control Strategy Enhancements

Innovative control strategies improve fault tolerance and decrease dynamic effects that can impact reliability:

- Digital Signal Processing (DSP) and Finite Element Simulations:

Integrating DSP-based control systems with finite element simulations allows for real-time monitoring and adjustment of current profiles. This dynamic adaptation protects the motor from sudden load changes and extreme temperature fluctuations.

- Multi-Criteria Decision-Making Models:

Techniques such as the Analytic Hierarchy Process (AHP) are used to evaluate different design parameters. These models assess the importance of torque density, efficiency, cost, and thermal performance to select the optimal design configuration for maximum reliability.

- Fault Detection and Diagnosis (FDD):

Advanced FDD systems utilize sensor arrays and real-time analytics to detect abnormal operating conditions before they lead to significant wear or failure. These systems are vital for initiating corrective actions and maintaining continuous safe operation.

7.4 Visualization: Engineering Strategies for Enhanced PMSM Reliability

Figure 4 presents a diagram summarizing the main engineering strategies used to enhance reliability of: Advanced Cooling Techniques, Material Optimization, Control Strategy Enhancements, Fault Detection and Diagnosis.

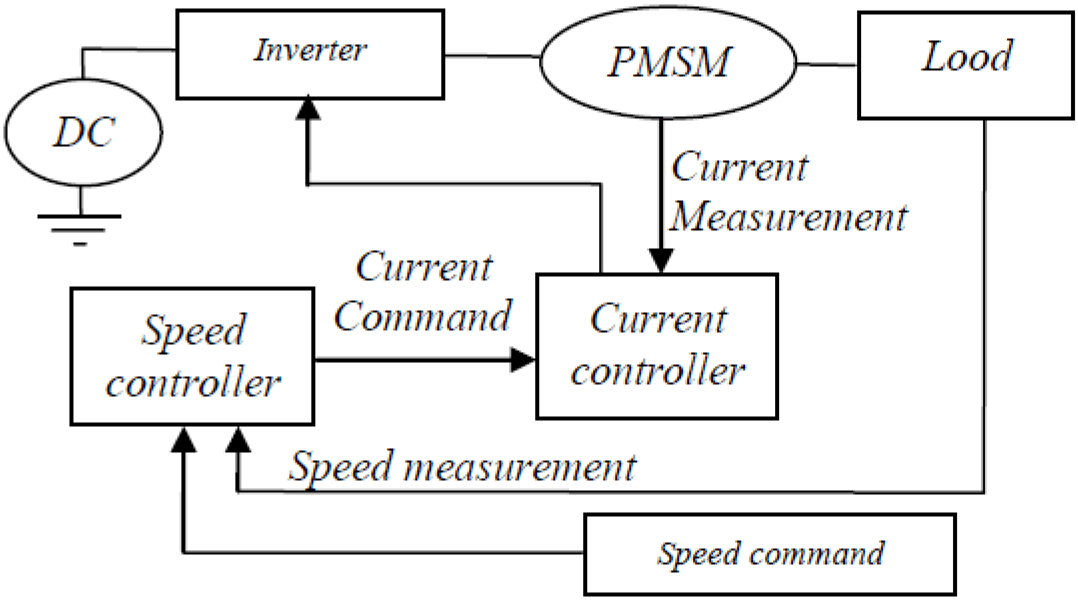

Figure (4) : Summary of Engineering Strategies for Enhanced PMSM Reliability.

This diagram highlights the comprehensive approach needed to improve the reliability of PMSMs, emphasizing the significance of thermal management, material choice, control improvements, and real-time fault detection.

8. Discussion

The comparative analysis above reveals a nuanced landscape for EV motor reliability. While PMSMs demonstrate clear advantages in efficiency, torque smoothness, and advanced fault-tolerant control methodologies, their overall system reliability heavily depends on effective thermal management and precise engineering designs. The main discussion points include:

• Interdependence of Design and Operation:

The reliability of a PMSM depends not only on its motor design but also on the interaction between operational conditions such as (dynamic load fluctuations and temperature variations) and the control strategies used. As supported by studies on dynamic reliability, achieving long-term reliability requires an integrated approach that addresses wear, thermal degradation, and electrical faults together.

• Comparative Trade-Offs:

Although BLDC motors offer a simpler mechanical design and easier control, their performance can be limited by torque ripple and reduced efficiency, especially under fluctuating loads. SRMs, despite their natural fault tolerance, need significant improvements in control methods to address issues like torque pulsation and noise. Induction motors, while durable and affordable, might sacrifice peak dynamic performance compared to PMSMs.

• System-Level Integration:

The integration of fault-tolerant strategies—such as dual-winding configurations and vector-based control algorithms—shows that PMSMs can attain exceptional reliability even in adverse conditions. However, system-level integration remains difficult due to diverse operating conditions, which require adaptive and individually optimized control schemes.

• Strategic Future Directions:

Research on reliability enhancement continues to develop, with future efforts likely to focus on synergistic approaches that combine improved materials, advanced cooling solutions, and real-time diagnostics. Multi-criteria decision-making models, which balance efficiency, cost, dynamic performance, and reliability, will become increasingly important in optimizing EV motor drives.

Taken together, the discussion highlights that while no single EV motor technology can claim complete superiority in all operating parameters, the PMSM stands out for offering high efficiency and strong fault tolerance—assuming its inherent design challenges are addressed effectively.

9. Conclusion

In conclusion, the comparative reliability study of PMSM versus other EV motor drives reveals several key insights.:

• High Efficiency and Smooth Operation:

PMSMs are characterized by their high efficiency and smooth torque output, which are essential for providing both performance and long-term reliability in EV applications.

• Critical Role of Thermal Management:

Temperature management remains critical, as high operating temperatures can significantly damage winding insulation, permanent magnets, and power electronics, ultimately affecting motor reliability.

• Advanced Fault Tolerant Control:

The use of innovative control strategies—including vector space decomposition, dual-winding designs, and Full Range Minimum Loss techniques—improves the fault tolerance and operational stability of PMSM systems, allowing them to operate under adverse conditions.

• Balancing Trade-Offs:

While BLDC, SRM, and induction motors provide alternative advantages in terms of design simplicity or cost, they often encounter challenges such as higher torque ripples and lower dynamic efficiency. As indicated in multi-criteria analyses, the reliability strengths of PMSMs are closely tied to meticulous engineering design and effective control.

• Reliability of PMSM

PMSM reliability is mainly affected by thermal management, wear, and dynamic loading. This is addressed by advanced fault-tolerant strategies, such as multi-phase and dual-winding designs, which significantly improve operational reliability.

The main findings can be summarized as follows: The differences in operating principles and design features result in varied reliability profiles among these motors. While PMSMs are known for smooth operation and high efficiency, issues like thermal management and failure mode interdependence require careful attention. Conversely, BLDC, IM, and SRM drives offer alternative advantages in cost or fault tolerance but often experience increased torque pulsations or vibrations.

10 Future works

Through a comprehensive analysis that combines dynamic reliability models, thermal assessments, and fault-tolerant control strategies, this article highlights that the choice of motor type must align with the specific design requirements and operating conditions of the electric vehicle application. Future research should continue refining these methods to ensure EV motor drive systems not only meet immediate performance goals but also maintain reliable operation throughout their lifecycle..

• Comparative studies indicate that while alternative motor types have their merits, PMSMs are preferred for high-performance EV applications, provided their design complexities are effectively managed. Currently, neodymium-based magnet (permanent magnet) technology dominates the market. However, in the future, there will be innovations in alternative materials to reduce reliance on the rare earth supply chain. Materials such as iron ferrite and iron nitride appear promising. Developing new grades of electrical Steel Magnet Composites (SMCs) that balance cost and performance is essential for making electric vehicles more affordable. These materials aim to provide higher magnetic permeability and lower losses.

• The manufacturers are researching lighter materials to reduce motor weight. Lighter electric vehicle motors enhance efficiency, range, and handling. Incorporating the motor into the body saves space and offers more flexible design options. Notably, there is a growing trend toward integrating non-magnetic motors as auxiliary drive units in all-wheel drive (AWD) vehicles.

• In advanced winding technologies such as hairpin winding, improvements in the charge factor and reductions in resistance enhance motor efficiency. Additive manufacturing of windings allows for more complex designs and optimized winding layouts, which improve thermal management and reduce material waste. Using materials like graphene or high-temperature superconductors (HTS) in windings can significantly boost conductivity and efficiency, although these technologies are still in the research phase.

• Additional integration with other subsystems, such as power electronics and software control systems, creates new opportunities to enhance safety, vehicle lifespan, and performance. Additionally, this system could showcase crashworthiness and high-performance capabilities if integrated with the noise, vibration, and harshness (NVH) system. Considering NVH during design aims to ensure a comfortable driving experience by personalizing the drive system.

• Digital technologies are crucial in the electric vehicle roadmap, covering design, manufacturing, and control. Artificial intelligence (AI) and data will play significant roles. Enhancing sustainability is challenging because varying levels of design and integration make disassembly and recycling difficult. New methods for extracting materials are necessary, especially as capacity increases and the value of the contained materials rises.

References

[1] Di Gerlando, Antonio, Massimiliano Gobbi, Maria Chiara Magnanini, Gianpiero Mastinu, Roberto Palazzetti, Aqeab Sattar, and Tullio Tolio. "Circularity potential of electric motors in e-mobility: methods, technologies, challenges." Journal of Remanufacturing 14, no. 2 (2024): 315-357.

[2] Greene, David L., Sangsoo Park, and Changzheng Liu. "Public policy and the transition to electric drive vehicles in the US: The role of the zero emission vehicles mandates." Energy Strategy Reviews 5 (2014): 66-77.

[3] Cunanan, Carlo, Manh-Kien Tran, Youngwoo Lee, Shinghei Kwok, Vincent Leung, and Michael Fowler. "A review of heavy-duty vehicle powertrain technologies: Diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles." Clean Technologies 3, no. 2 (2021): 474-489.

[4] Kapustin, Nikita O., and Dmitry A. Grushevenko. "Long-term electric vehicles outlook and their potential impact on electric grid." Energy Policy 137 (2020): 111103.

[5] Kashem, Mohammad Abul, Mohammad Shamsuddoha, and Tasnuba Nasir. "Sustainable transportation solutions for intelligent mobility: a focus on renewable energy and technological advancements for electric vehicles (EVs) and flying cars." Future Transportation 4, no. 3 (2024): 874-890.

[6] Roy, Dhanush, and Chin Chun Kumar. "A Comprehensive Analysis of the Reliability of Electric Vehicle Motor Systems: Exploring the Intricacies of Performance and Durability."

[7] Yang, Yang, Qiang He, Chunyun Fu, Shuiping Liao, and Peng Tan. "Efficiency improvement of permanent magnet synchronous motor for electric vehicles." Energy 213 (2020): 118859.

[8] Zhao, Pinzhi, and Guijie Yang. "Torque density improvement of five-phase PMSM drive for electric vehicles applications." Journal of Power Electronics 11, no. 4 (2011): 401-407.

[9] Prabhu, Nagesh, R. Thirumalaivasan, and Bragadeshwaran Ashok. "Critical review on torque ripple sources and mitigation control strategies of BLDC motors in electric

vehicle applications." IEEE Access 11 (2023): 115699-115739.

[10] Lan, Yuanfeng, Yassine Benomar, Kritika Deepak, Ahmet Aksoz, Mohamed El Baghdadi, Emine Bostanci, and Omar Hegazy. "Switched reluctance motors and drive systems for electric vehicle powertrains: State of the art analysis and future trends." Energies 14, no. 8 (2021): 2079.

[11] Azab, Mohamed. "A Review of Recent Trends in High-Efficiency Induction Motor Drives." Vehicles 7, no. 1 (2025): 15.

[12] Sanghai, Neha Sukhanand, and Prakash G. Burade. "A comprehensive review of electric motors used in EVs." In AIP conference proceedings, vol. 3156, no. 1, p.

[13] Ahmad, Shahid. "Key Factors in Automobile Design: Expert Views on Enhancing User Experience during New Product Development." Educational Administration: Theory and Practice 30, no. 5 (2024): 13145-13156.

[14] Dharmakeerthi, C. H., N. Mithulananthan, and A. Atputharajah. "Development of dynamic EV load model for power system oscillatory stability studies." In 2014 Australasian Universities Power Engineering Conference (AUPEC), pp. 1-6. IEEE, 2014.

[15] Khan, MY Ali. "Enhancing electric vehicle performance: A case study on advanced motor drive systems, integration, efficiency, and thermal management." Control Systems and Optimization Letters 3, no. 1 (2025): 20-27.

[16] Un-Noor, Fuad, Sanjeevikumar Padmanaban, Lucian Mihet-Popa, Mohammad Nurunnabi Mollah, and Eklas Hossain. "A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development." Energies 10, no. 8 (2017): 1217.

[17] Pellegrino, Gianmario, Alfredo Vagati, Barbara Boazzo, and Paolo Guglielmi. "Comparison of induction and PM synchronous motor drives for EV application including design examples." IEEE Transactions on industry applications 48, no. 6 (2012): 2322-2332.

[18] Hegde, Ramakrishna N., Naresh Choudhary, K. Sathwik, N. Jagadeesha, and Bhavish Shetty. "Design and analysis of PMSM and controller for electric vehicle." In AIP Conference Proceedings, vol. 3299, no. 1, p. 030003. AIP Publishing LLC, 2025.

[19] Sundaram, Maruthachalam, Mouttouvelou Anand, Jaganathan Chelladurai, Paramasivam Varunraj, Sam Joshua Smith, Shubham Sharma, Mamdouh El Haj Assad, and Reza Alayi. "Design and FEM Analysis of High-Torque Power Density Permanent Magnet Synchronous Motor (PMSM) for Two-Wheeler E-Vehicle Applications." International Transactions on Electrical Energy Systems 2022, no. 1 (2022): 1217250.

[20] Abd Aziz, Mohd Azri, Mohd Saifizi Saidon, Muhammad Izuan Fahmi Romli, Siti Marhainis Othman, Wan Azani Mustafa, Mohd Rizal Manan, and Muhammad Zaid Aihsan. "A review on BLDC motor application in electric vehicle (EV) using battery, supercapacitor and hybrid energy storage system: efficiency and future prospects." J. Adv. Res. Appl. Sci. Eng. Technol 30, no. 2 (2023): 41-59.

[21] Mohanraj, Deepak, Ranjeev Aruldavid, Rajesh Verma, K. Sathiyasekar, Abdulwasa B. Barnawi, Bharatiraja Chokkalingam, and Lucian Mihet-

Popa. "A review of BLDC motor: state of art, advanced control techniques, and applications." Ieee Access 10 (2022): 54833-54869.

[22] Rambabu, S. "Modeling and control of a brushless DC motor." Master of Thesis in Power Control and Drives Technology, National Institute of Technology Rourkela (2007).

[23] Hannon, Bert, Peter Sergeant, and Luc Dupré. "Evaluation of the torque in high-speed PMSMs with a shielding cylinder and BLDC control." IEEE Transactions on Magnetics 54, no. 10 (2018): 1-8.

[24] Prabhu, Nagesh, R. Thirumalaivasan, and Bragadeshwaran Ashok. "Critical review on torque ripple sources and mitigation control strategies of BLDC motors in electric vehicle applications." IEEE Access 11 (2023): 115699-115739.

[25] Krishnamoorthy, Sreeram, and P. Parakkat Kesava Panikkar. "A comprehensive review of different electric motors for electric vehicles application." Int. J. Power

[26] Mousavi-Aghdam, Seyed Reza, Mohammad Reza Feyzi, Nicola Bianchi, and Mattia Morandin. "Design and analysis of a novel high-torque stator-segmented SRM." IEEE Transactions on Industrial Electronics 63, no. 3 (2015): 1458-1466.

[27] Fang, Gaoliang, Filipe P. Scalcon, Dianxun Xiao, Rodrigo P. Vieira, Hilton A. Gründling, and Ali Emadi. "Advanced control of switched reluctance motors (SRMs): A review on current regulation, torque control and vibration suppression." IEEE Open Journal of the Industrial Electronics Society 2 (2021): 280-301.

[28] Li, Sufei, Shen Zhang, Thomas G. Habetler, and Ronald G. Harley. "Modeling, design optimization, and applications of switched reluctance machines—A review." IEEE Transactions on Industry Applications 55, no. 3 (2019): 2660-2681.

[29] Wen, Jinyu. "PSO and GA designed pareto of fuzzy controller in ac motor drive." International Journal of Control and Automation 6, no. 5 (2013): 149-158.

[30] Ferreira, Fernando JTE, Ge Baoming, and Aníbal T. de Almeida. "Reliability and operation of high-efficiency induction motors." In 2015 IEEE/IAS 51st Industrial & Commercial Power Systems Technical Conference (I&CPS), pp. 1-13. IEEE, 2015.

[31] Azom, Md Ali, and Md Yakub Ali Khan. "Challenges and Advances in Electrical and Thermal Modeling of High-Precision PMSM Drives." Control Systems and Optimization Letters 3, no. 2 (2025): 130-137.

[32] Ammaiyappan, Bharathi Sankar, and Seyezhai Ramalingam. "Reliability investigation of electric vehicle." Life Cycle Reliability and Safety Engineering 8, no. 2 (2019): 141-149.

[33] Wang, Wei, Gang Shen, Yimin Zhang, Zhencai Zhu, Changyou Li, and Hao Lu. "Dynamic reliability analysis of mechanical system with wear and vibration failure modes." Mechanism and Machine Theory 163 (2021): 104385.

[34] Jiang, Song, Wei Li, Gaifang Xin, Lianchao Sheng, and Yuqiao Wang. "Study dynamic reliability of permanent magnet gear transmission system with wear and failure correlation." Engineering Failure Analysis 131 (2022): 105802.

[35] Vassilopoulos, Anastasios P., ed. "Fatigue life prediction of composites and composite structures." (2019).

[36] Braut, Sanjin, Eerik Sikanen, Janne Nerg, Jussi Sopanen, and Željko Božić. "Fatigue life prediction of Electric RaceAbout

(ERA) traction motor rotor." Procedia structural integrity 31 (2021): 45-50.
[37] Khan, MY Ali. "Enhancing electric vehicle performance: A case study on advanced motor drive systems, integration, efficiency, and thermal management." Control Systems and Optimization Letters 3, no. 1 (2025): 20-27.
[38] Ghaedi, Amir, Mehrdad Mahmoudian, and Reza Sedaghati. "The impact of the speed and temperature variation on the electric vehicles' reliability." International Transactions on Electrical Energy Systems 2022, no. 1 (2022): 4876218.
[39] Zhou, Peng, Yanliang Xu, and Feng Xin. "Study of magneto-thermal problems in low-speed high-torque direct drive PMSM based on demagnetization detection and loss optimization of permanent magnets." IEEE Access 11 (2023): 92055-92069.
[40] Abuelnaga, Ahmed, Mehdi Narimani, and Amir Sajjad Bahman. "A review on IGBT module failure modes and lifetime testing." IEEE access 9 (2021): 9643-9663.
[41] Choi, Chinchul, and Wootaik Lee. "Fault diagnosis and tolerance on reliability of automotive motor control system: a review." International Journal of Automotive Technology 23, no. 4 (2022): 1163-1174.
[42] Sun, Pengcheng, Shaofeng Jia, Deliang Liang, and Ronghai Qu. "A review on the development of high-reliability motor system for safety-critical applications—From redundancy design prospective." IEEE Transactions on Transportation Electrification 10, no. 3 (2023): 7374-7388.
[43] Gao, ChaoFan, Hongyu Zheng, and Chuyo Kaku. Design of Fault-Tolerant Control Strategy for Dual-Winding Permanent Magnet Synchronous Motor in Vehicles. No. 2025-01-8805. SAE Technical Paper, 2025.
[44] Orlowska-Kowalska, Teresa, Marcin Wolkiewicz, Przemyslaw Pietrzak, Maciej Skowron, Pawel Ewert, Grzegorz Tarchala, Mateusz Krzysztofiak, and Czeslaw T. Kowalski. "Fault diagnosis and fault-tolerant control of PMSM drives–state of the art and future challenges." Ieee Access 10 (2022): 59979-60024.
[45] Akin, Bilal, Salih Baris Ozturk, Hamid A. Toliyat, and Mark Rayner. "DSP-based sensorless electric motor fault-diagnosis tools for electric and hybrid electric vehicle powertrain applications." IEEE Transactions on Vehicular Technology 58, no. 6 (2009): 2679-2688.
[46] Song, Yantao, and Bingsen Wang. "Evaluation methodology and control strategies for improving reliability of HEV power electronic system." IEEE Transactions on Vehicular Technology 63, no. 8 (2014): 3661-3676.
[47] Khalid, S. "A comprehensive review of advanced control strategies for hybrid electric vehicles." Hybrid Electric Vehicles and Distributed Renewable Energy Conversion: Control and Vibration Analysis (2025): 55-98.
[48] Mohanraj, Deepak, Janaki Gopalakrishnan, Bharatiraja Chokkalingam, and Lucian Mihet-Popa. "Critical aspects of electric motor drive controllers and mitigation of torque ripple." IEEe Access 10 (2022): 73635-73674.
[49] Yang, Yifei, Yilong Wen, Xiaodong Sun, and Renzhong Wang. "Overview of Fault-Tolerant Control for Switched Reluctance Motor Drive Systems." Journal of Electrical Engineering & Technology (2025): 1-24.
[50] Bello, Abdulaziz, Ibrahim Muhammad Kilishi, Muntaka

Musa Bari, and Usman Abubakar. "Comparative Review of PMSM And BLDCM Based on Direct Torque Control Method." International Journal of scientific & technology research 3, no. 3 (2014): 195-199.

[51] Rafaq, Muhammad Saad, Will Midgley, and Thomas Steffen. "A review of the state of the art of torque ripple minimization techniques for permanent magnet synchronous motors." IEEE Transactions on Industrial informatics 20, no. 1 (2023): 1019-1031.