

Review

Essential Features and Torque Minimization Techniques for Brushless Direct Current Motor Controllers in Electric Vehicles

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Abstract: The use of electric automobiles, or EVs, is essential to environmentally conscious transportation. Battery EVs (BEVs) are predicted to become increasingly accepted for passenger vehicle transportation within the next 10 years. Although enthusiasm for EVs for environmentally friendly transportation is on the rise, there remain significant concerns and unanswered research concerns regarding the possible future of EV power transmission. Numerous motor drive control algorithms struggle to deliver efficient management when ripples in torque minimization and improved dependability control approaches in motors are taken into account. Control techniques involving direct torque control (DTC), field orientation control (FOC), sliding mode control (SMC), intelligent control (IC), and model predictive control (MPC) are implemented in electric motor drive control algorithms to successfully deal with this problem. The present study analyses only sophisticated control strategies for frequently utilized EV motors, such as the brushless direct current (BLDC) motor, and possible solutions to reduce torque fluctuations. This study additionally explores the history of EV motors, the operational method between EM and PEC, and EV motor design techniques and development. The future prospects for EV design include a vital selection of motors and control approaches for lowering torque ripple, as well as additional research possibilities to improve EV functionality.



Citation: Tabassum, A.A.; Cho, H.M.; Mahmud, M.I. Essential Features and Torque Minimization Techniques for Brushless Direct Current Motor Controllers in Electric Vehicles.

Energies **2024**, *17*, 4562. <https://doi.org/10.3390/en17184562>

Academic Editor: Chunhua Liu

Received: 7 August 2024

Revised: 6 September 2024

Accepted: 9 September 2024

Published: 12 September 2024



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Keywords: brushless DC motor; torque ripple; electric vehicle motor design; motor control techniques

1. Introduction

Since the beginning of the twentieth century, emissions of greenhouse gases, such as carbon dioxide (CO₂), hydrocarbons, nitrous oxide, sulfur dioxide, oxides of nitrogen, and methane, have been contributing extensively to an upward trend in the contamination of the environment. The automotive engine is combined with a less carbon-intensive power industry, as seen in Figure 1. Electric vehicles (EVs) have no carbon footprint and are more productive than internal combustion engine vehicles (ICEVs), offering enormous promise for cutting CO₂ gasoline releases [1–7]. Even though EVs provide a viable way to lessen dependency on fossil fuels and greenhouse gas emissions, problems such as torque ripple in BLDC motors still exist [8]. In order to minimize torque ripple, this review intends to thoroughly explore and assess the advanced control strategies—DTC, FOC, and MPC—applied to BLDC motors [9]. The review also advances the subject by comparing these tactics to industry norms and addressing how well they work with the current generation of commercial EVs. The results give recommendations for future advancements in motor control technology for next-generation electric vehicles and shed light on the trade-offs associated with these control strategies.

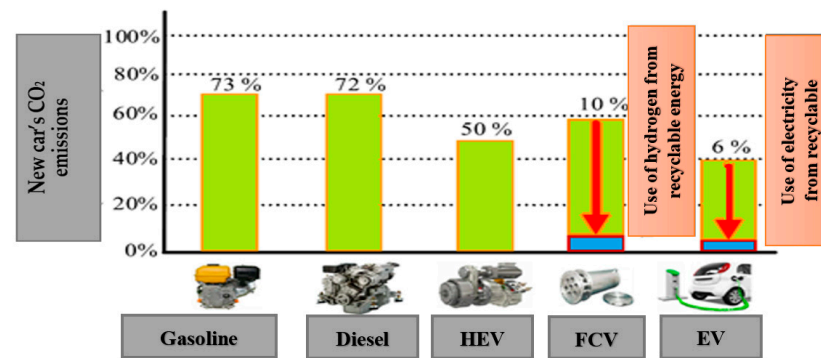


Figure 1. CO₂ concentrations by car engine type [7].

Electric motor technology offers a number of advantages and disadvantages for powering a powertrain over an extended length of time. The auto manufacturing sector has changed the design of several motors and their control methods throughout the past 10 years [10–14]. The key benefit of BLDC motors is their immense torque and power densities [15]. Controlling difficulty, ripple in the torque, EMI, fault-tolerant capabilities, sound disturbance in the field, decreasing capacity, and the excessive expense of PM components are the primary problems with BLDC traditional and in-wheel engines [16,17]. The authors of [18,19] talked about using PMSM to achieve the extreme torque and high density of power needed for EVs. Neodymium, an expensive PM rare earth element, is the primary problem. Low-cost ferrite is a good solution to mitigate this issue, although its energy and resistance are poor. Modern structure spoke, axial, in-wheel, and PM-aided motors are suggested as efficiency improvements [20,21]. PM structure and affordable PMSM elements are covered in this review. Both stator and rotor component losses are significant in [22–25] non-magnet inexpensive induction motors, as they lower effectiveness and tolerance to faults. According to Article [26,27], alternative electric motors with great fault-tolerant characteristics, resilience, high efficiency, and small dimensions, including the synchronous reluctance motor (SynRM), are also appropriate for EV power systems. The reluctance motor's variability, density of power, and power factor were the primary issues discussed in [27,28]. Table 1 lists the most promising EV motors based on their most widely used control systems.

Table 1. A thorough comparison of the characteristics of electric vehicle motors [16–27].

EV Motors	Key Challenges	Control Techniques	Design Topology
BLDC	High-cost magnet, torque ripples, reliability issues, (EMI, acoustic noise, fault Tolerant), Less efficiency.	FOC, DTC, MPC, intelligent controller and sensorless controller.	Opening stator slot wedges, Changing magnet pole area width position, interior rotor (surface mounted, buried, inserted in-wheel motor).
PMSM	High-cost magnet (Neodymium, samarium), demagnetization, Torque ripple, fault tolerant.	Low-cost ferrite material, FOC, DTC–SVM, MPC–PTC, SMC, intelligent controller, and sensorless controller.	PMA synRM, PM Axial flux motor, PM spoke type motor.

Table 1. *Cont.*

EV Motors	Key Challenges	Control Techniques	Design Topology
IM	Material loss (Al, Cu), High core loss, Low efficiency.	High conductivity material, material cost trade off, Sensorless control, FOC, DTC, and MPC-PTC.	Increased axial length, modeling skewed rotor.
BLDC	Less torque density, high acoustic noise, and vibration, High torque ripple.	TSE, DTC, DITC, MPC, FOC, MPC, SMC, and intelligent controller.	Increasing stator and rotor poles, axial flux SRM, optimize stator/rotor pole area, and length.

Direct torque control (DTC) was discussed in Article [29]. Its primary benefit is a greater dynamic response, and it has an easy-to-understand structure for both conventional and in-wheel motors. Although it produces a large ripple in torque and current, DTC is recommended for highly dynamic applications. Although it has yet to be demonstrated, Article [30] proposed field orientation control (FOC) to provide appropriate steady-state behavior over the whole load torque and speed restrictions. For in-wheel motors, Article [12] presented a unique duty-cycle model predictive control (MPC) in conjunction with a revolutionary finite-set phase-locked loop (PLL) sensorless scheme that enhances the system's resilience and dynamic performance. Without requiring a modulator, Article [13] presented a finite-set MPC that enhances both steady-state and dynamic performance by combining the virtual vector and duty cycle. Article [31] examined the in-wheel motor's fault-tolerant system following an error and proposed a fault-tolerant MPC approach utilizing a simulated vector that eliminates the standard scheme's complicated controller topology resetting and has high fault-tolerant efficiency. A sliding mode controller (SMC) is a resilient nonlinear system that applies high switching control to the dynamics of a nonlinear system, as stated in Article [32]. Article [33] made recommendations for advanced tolerance to faults, induction motor control, speed and torque responses, and high-performance EV/HEV applications based on modern intelligent controllers. For traction motor applications, Article [34] proposed using an effective rotor position estimation technique employing sensorless or model-based control over the complete speed range.

2. Classification of Electric Vehicles

Battery electric vehicles (BEVs) rely only on batteries [35–37]. Since they use an electric motor to rotate the wheels, they emit no pollution. Plug-in Hybrid Electric Vehicles (PHEVs) may operate on petrol or diesel for longer distances and have a zero-emission range of between 20 and 30 miles, according to [35]. A basic comparison is shown in Table 2.

Table 2. Sources and characteristics of electric vehicles [36,37].

EV List	Examples of EV	Problems	Features
BEV	• Tesla model 3 • BMW i3 • Nissan leaf • Tesla X	• Battery range capacity and high price. • Charging time increasing. • Need more charging stations. • Maximum price.	• No air emission. • Oil independent. • Battery range is high and large. • Commercially available.

Table 2. Cont.

EV List	Examples of EV	Problems	Features
HEV	• Honda civic • Toyota prius • Toyota camry	• Optimization. • Battery and engine size big. • Management of the energy sources is difficult.	• Emission is very less. • Battery range is long. • Both electric and fuel supply.
PHEV	• Audi A3 E-tron • BMW i8 • Chevy volt • Kia optima • Ford fusion	• Optimization. • Battery charge from an external source. • Battery and engine size are big. • Management of the energy sources is difficult.	• Low operating cost. • Maintain low air quality. • Reduced atmosphere gas emission. • Reduced noise.
FCEV	• Toyota mirai • Hyundai tucson • Honda clarity • Hyundai nexa	• Fuelling facilities availability check. • Cost of the fuel cell is high. • Safe way to produce fuel.	• Low emission. • Efficiency is high. • Price is high. • Commercially available. • No need for electricity.

Fuel cell EVs generate energy by splitting electrons from hydrogen molecules to power the motor. The battery attached to the gas cell serves as an extra energy source and emits no pollutants [35]. Battery energy is used to power an internal combustion engine and one or more electric motors in hybrid electric automobiles (HEVs) [36,37].

According to [38], the primary components of an electric vehicle's powertrain are electrical machines (EMs) for movement, power electronic converters (PECs), and innovative storage of energy sources, including fuel cells, power sources, and supercapacitors. The authors of [39] presented an integrated energy management system capable of supplying energy from several emission-free sources, such as petroleum, organic matter, natural gas, fossil fuels, nuclear, hydropower, wind, and solar. Figure 2 illustrates the relationship between EM and PEC, as well as the bidirectional power flow between acceleration and deceleration modes for regenerative braking in EVs to boost battery energy.

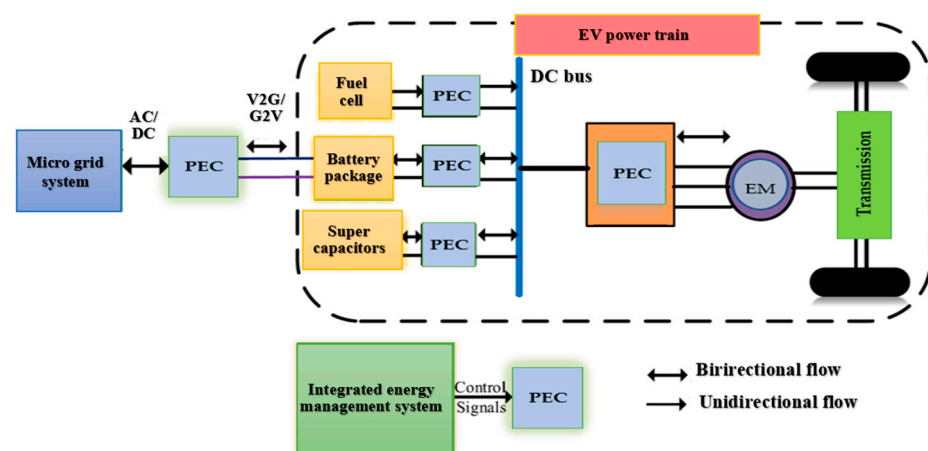


Figure 2. New sources of energy storage [38,39].

As seen in Figure 3, the four interconnected parts that make up an EV's structure are the electric motor, energy converter, controller, and energy storage (battery) [38,40].

Electrical machines have been powering electric vehicles (EVs) for the past 50 years by using motors with low cogging torque (BLDC), low-cost components within PMSMs, improved efficiency (IMs), and torque-ripple-free SRMs.

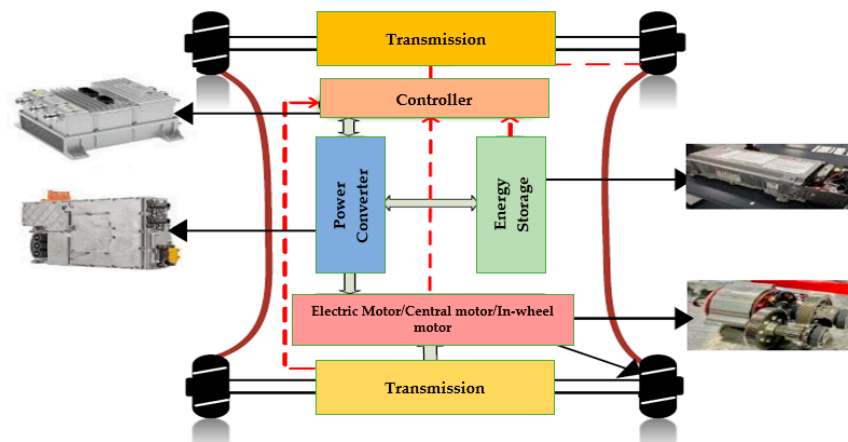


Figure 3. The development of electric vehicles [38,40].

Power electronic converters, which select chopper, inverter, and resonant converters depending on the energy preservation distribution system converter, were utilized in [41] to transform the origin of the input.

3. BLDC (Brushless DC Motor)

The most appropriate motors are those depicted in Table 3, which is based on a thorough review of the literature and current studies in the automotive sector that specifically employ EV features. BLDC motors are efficient, reliable, and maintenance free, with high torque-to-weight ratios, quiet operation, and electronic commutation, making them ideal for various high-performance applications [38,39,42–45].

Table 3. The development of electric vehicles [38,39,42–45].

EV Motors	BLDC	IPMSM	ACIM
EV Company	• Ather Energy • Scooters • Yamaha EC-03 • Upcoming TVS	• Soul EV • Nissan Leaf • Toyota Prius	• GM EV1 • Toyota RAV4 • Tesla Model X • Tesla Model S
Advantages	• High torque density • No rotor copper loss • Small size and lighter • Better heat dissipation • High reliability • Specific power is high	• Efficiency is high • Specific torque • Density is high • High power density	• Ruggedness • Maximum peak torque • Dynamic response is good • Less maintenance
Disadvantages	• PM rare earth material • Cost is high • Constant power range less • High cogging and reluctance torque ripple • Decreased with increase in drive speed	• Iron loss maximizes at high speed through in wheel operation • Demagnetization • High cost material	• Less efficiency • Copper loss

3.1. Characteristics of BLDC Motors

The primary drawbacks of BLDC include its expensive Permanent Magnet (PM) substance, limited velocity spectrum, ripples in the torque, low efficiency, tolerance for faults, and disruption from electromagnetic waves. There are four different earth materials that may be used: low-cost ferrite, permanent NdFeB, big corrective force and greatest density SmCo, and high temperature capacity Alnico, which can be used to categorize the production of a motor utilizing PM material [14]. Currently, writers have addressed high demagnetization, rich permanence, excessive energy density, and corrective force [14,45]. PM materials are generally mixed with additional substances, such as samarium alloys and neodymium magnet alloys. In [46], PM materials including ferrite and Alnico were reported to have an impact on the torque intensity and demagnetization capability. Nonetheless, Ferrite (Fe) has the highest field-limiting capacity and spins at its fastest rate when it comes to minimal coercivity, as described by the authors of [46]. Iron oxide magnet alloys are a common, inexpensive, and free material for the BLDC drive's inner and hub. Prior to choosing a superior EV motor, [47] suggested examining the material's physical characteristics and driving parameters. According to [48], the output design of EVs is predicated on a rigorous examination of their geometric properties. Because of how well EVs operate in terms of speed–torque features, BLDC is primarily utilized in tiny cars with a maximum output of 30 kW.

In [48,49], the authors discussed BLDC hub motors. As seen in Figure 4, permanent magnets are mounted on a circle outside the stator coils, forming the rotor. The rotor remains static, while the ring of magnets is kept in circulation. For lightweight EVs, hub motors are recommended because it is simple to mount a wheel over them. Using hub motors has three primary drawbacks: (i) increasing the amount of mass on the power-driven side, which reduces vehicle stability, (ii) making consistent torque delivery too difficult, and (iii) incurring more mechanical stress than typical BLDC motors.

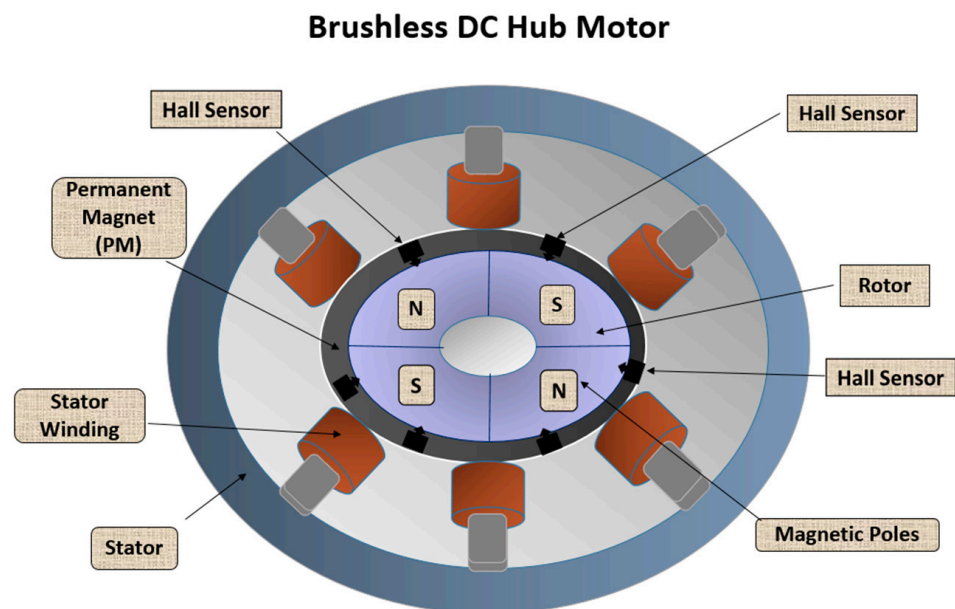


Figure 4. BLDC hub motor [48–50].

As seen in Figure 5, the recommended PM in [50] is attached to a ring on the inner side of the stator wires. The ring moves while the stator, known as the internal rotor, remains static.

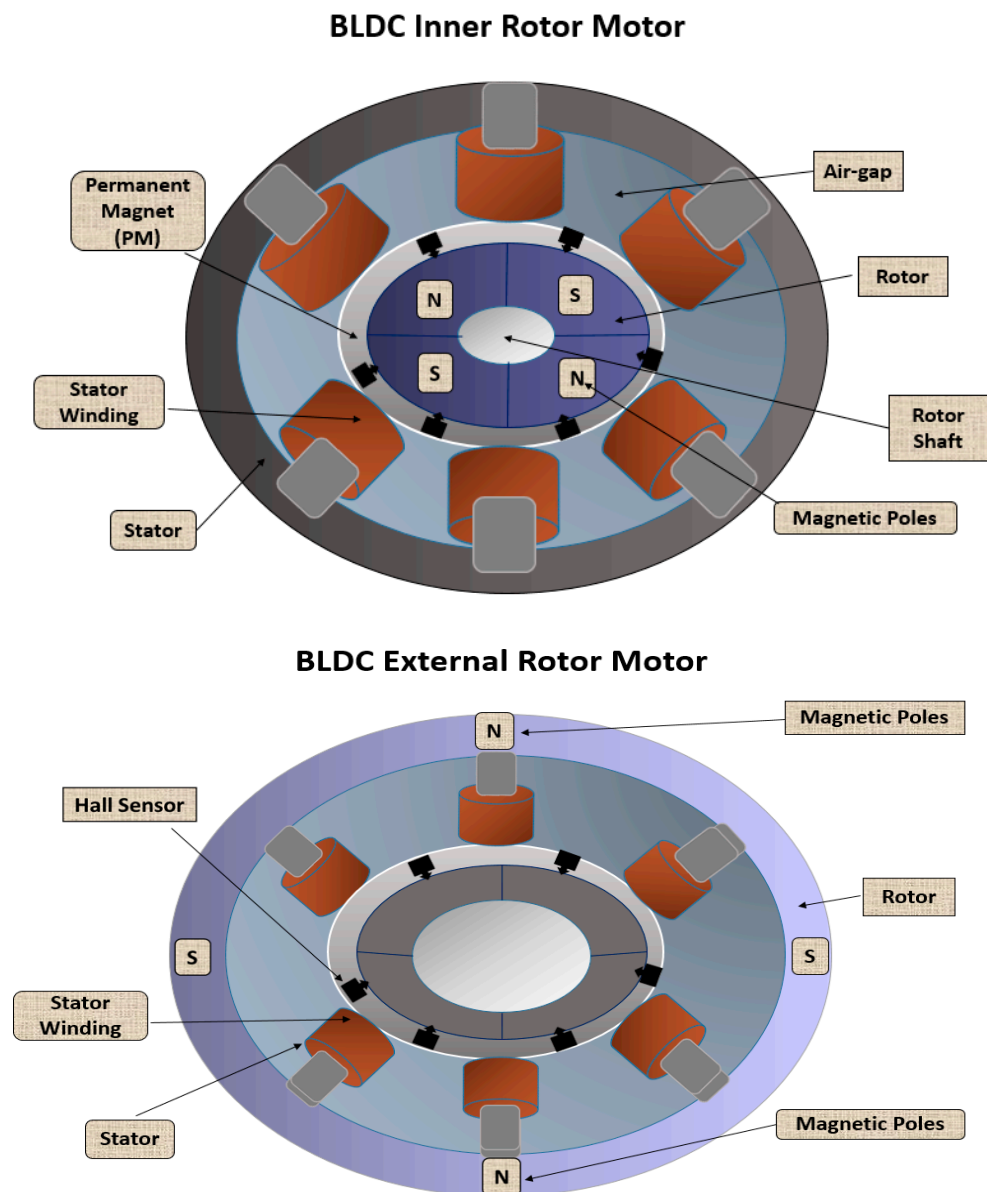


Figure 5. BLDC inner rotor motor and external rotor motor [48–50].

Since there are no windings on the rotor side, the BLDC used in [17] has a trapezoidal back EMF waveform, which lowers copper loss and boosts efficiency. An electronic commutator, voltage supply, inverter, and sensor are features of BLDC drives, which operate in a constant power area, producing the highest torque per ampere. The authors of [17,30,51] covered vector control, direct torque control, and indirect torque control as methods of controlling motor speed above the base speed.

The primary baseline power rating used in BLDC EV drives means that the BLDC outer rotor type in Figure 5 produces smaller torque ripples than the BLDC inner rotor type. Figure 6 illustrates how the nature of BLDC may produce various torque ripples [52].

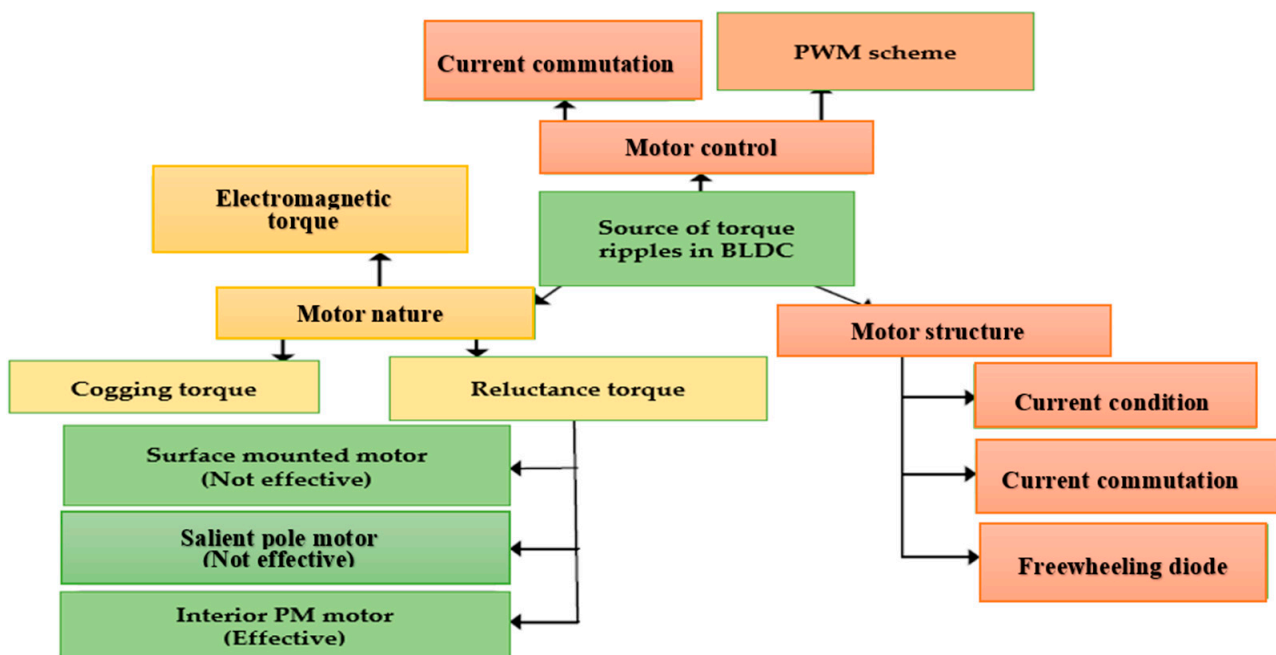


Figure 6. Origin of BLDC torque ripples [51].

3.1.1. Power Density of BLDC Motors

BLDC motors are well known for their great power density, making them ideal for applications in EVs where space and weight are precious. The use of permanent magnets in the rotor allows for a more compact design while producing greater torque and power per unit size than induction motors. This advantage is critical for EVs, since it allows for more effective use of battery power, which increases the vehicle's operating range. Studies suggest that BLDC motors may attain a power density of up to 5 kW/kg, which is much greater than that of standard induction motors, making them perfect for small EV designs [53].

Meanwhile, relying on rare-earth magnets to achieve high power density has limitations because of their expensive cost and unpredictable supply. This can have an influence on the overall cost of the motor as well as on the cost of the EVs powered by these motors [54].

3.1.2. Cost-Effectiveness of BLDC Motors

BLDC motors are more cost-effective in the long run because of their high efficiency and reduced maintenance needs. The removal of brushes minimizes mechanical wear and the need for frequent replacements, resulting in cheaper operating and maintenance expenses. This feature makes BLDC motors especially appealing for EV applications, where lowering the total cost of ownership is crucial [55].

The initial cost of BLDC motors might be greater than that of other motor types owing to the expense of permanent magnets. The high cost of materials such as neodymium magnets, which are required for the requisite magnetic characteristics, might be a considerable hurdle. Variations in the quantity and cost of rare-earth minerals can further challenge cost management [56].

4. Control Techniques for the Torque Ripple in BLDC Motors

It was stated in [51,57] that torque ripples are produced by a reverse EMF spread non-sinusoidal pulse when there is a BLDC gap in the air across the slot field magnet and the flux coupling. Both the inner and outer rotors of the EV develop vibrations and sounds. Due to this influence, the motor operates at low power, resulting in overburden limit impacts generated by rotor magnetism. This has led to research into various control

strategies to lessen torque ripples. The author of [51] described how BLDC produces the least amount of torque ripple by having commutation angles every 60 degrees and irregularly circulating helices in the air space magnetic field. Control techniques using pulse width modulation (PWM) were employed to remove ripples in torque caused by the magnetic field of the stator. The impacts of the PWM mode on the torque rippling associated with the commutation switching angle were reduced in the suggested sensorless controller [58]. To lessen the torque ripple during the turn-off procedure, the PWM control approach uses BEMF to generate current. For motors with low power ratings, the PWM chopping approach reduces torque ripples.

The PWM cutting approach and the overlapped method are both switching techniques used in [58] to reduce torque fluctuation. The suggested approach in [58] has a supply voltage that results in torque ripples and fewer current ripples in the conduction field. The conduction ripple of torque in BLDC is eliminated by using cascade buck converters, one of the alternative control strategies. In PWM techniques, the duty cycle is adjusted to smooth out the current waveform and minimize torque ripple [59]. In addition, MPC is an advanced method that uses a model of the motor to predict and minimize torque ripple dynamically [60].

By altering the voltage at the input, the suggested BLDC ripple of torque in [41] may be made smaller, which also reduces the current fluctuation. In the current absorption zone, the BEMF remains constant, but the torque ripple is contingent upon the current ripple. The amount of torque ripple is decreased in [61] by the two switching current assessment strategies suggested: direct current sensing-based synchronization and the lack of negative DC voltage. The multi-objective optimization method described in [62] will equalize the current slope curves of both the inward and outward phases during the commutation period if appropriate duty ratio control is used. The basis of the suggested approach to lessen the ripple effect of torque in [61] is the advancement step angle system of controls. The torque magnitude ripple is reduced by using the rectangular-shaped current phase waveform, utilizing the velocity and torque reaction features approach.

The electromagnetic torque generated in a BLDCM is determined by the DTC flux couplings connecting the stator and rotor perspectives [63]. Therefore, DTC is able to offer an extreme response that is dynamic. The DTC approach is primarily utilized for EV gears in [64,65] to minimize commutation force fluctuation. Lowering the gap within the reference instruction and the predicted torques is how the method operates. Commutation ripples due to torque are efficiently eliminated by the DTC phase current waveform modification in steady-state electromagnetic torque flux, especially at high rotational speeds. The goal of the idea stated by the author of [66] is to accomplish continuously adjustable gearboxes in EVs. Instead of utilizing multiple current sensors to determine the DC bus current, the automation system employs just one current sensor to provide traction control. For electromechanical variable gearboxes, consistent power, as well as torque, may be obtained by choosing closed-loop control of torque with phase advanced angle and field weakening. An oscillation index was used in [67] to measure the ripples in the suggested reluctance torque, and an FEA simulation was employed for the computation task. The reduction of torque ripple by a wide-angle wave modulation technique was discussed by the authors of [61,68].

The novel intelligent control system proposed in [69] consists of two fuzzy controllers that work together to create an intricate system. The first controller is intended to choose the appropriate voltage vector control algorithm depending on acceleration error, and the second one minimizes acceleration error by taking into account the stator flux linkage perspective and electric error. The phase synchronization in [70] considers that fuzzy controlling reduces the overall resonance of torque in a BLDC motor. By replacing the conventional speed PID controller with a fuzzy PI controller, it is possible that the EV drive powertrain technique's effectiveness may be enhanced by lowering torque ripple. The least common multiple (LCM), which is suggested to minimize the ripples in torque, is an integer multiple of each of the rotor's and stator's pole values.

FOC uses precise control of the magnetic field to reduce torque ripple [71]. It involves controlling the magnetic field of the motor to align with the rotor flux, thus optimizing torque production [72]. Ref. [73] states that PWM may be used in FOC in a variety of methods, including IFOC. When compared to DTC, the best-known methods that aid in reducing torque ripple include sinusoidal PWM, space vector PWM, and third harmonic injection PWM. Evolutionary algorithms, neural networks, and fuzzy logic are a few examples of soft computing techniques that may be used in situations demanding the highest level of precision and control schemes for EV drives to reduce torque fluctuation [74]. The comparison in Table 4 below visually summarizes the differences in control strategies across various EV models.

Table 4. Comparison table of control strategies in commercial EVs [71,72,74].

Control Strategy	Tesla Model S/3	BMW i3	Audi e-Tron
FOC	Used for high efficiency and smooth torque control across speeds.	Not used.	Not used.
DTC	Not used.	Used for dynamic torque management.	Not used.
MPC	Not used.	Not used.	Used for real-time optimization and energy efficiency.

The most common problems with the use of BLDC in EVs are rippling torque, electro-magnetic disturbance, and fault tolerance. Applying advanced control techniques, such as DTC and complex control, may minimize these. Table 5 shows the hypothetical numerical values based on common findings, and Table 6 lists all of their attributes in detail.

Table 5. Table of torque ripple mitigation [59,60,71,75].

Technique	Low Speed, Low Load (Torque Ripple %)	Low Speed, High Load (Torque Ripple %)	High Speed, Low Load (Torque Ripple %)	High Speed, High Load (Torque Ripple %)
PWM (Traditional)	12%	15%	18%	22%
Field-Oriented Control (FOC)	6%	8%	10%	12%
Hysteresis Current Control (HCC)	5%	7%	9%	11%
Model Predictive Control (MPC)	4%	5%	7%	9%

Table 6. Methods for controlling torque fluctuations [73].

Method	Adapted Techniques	Advantages	Disadvantages
Modified PWM control	• PWM chopping method. • Low-cost digital control technique.	• Higher output torque lower ripples. • Minimum cost.	• Eliminating only torque ripple caused by stator magnetic field.
DC bus voltage control	• Cascade buck converter	• Reduce torque ripples. • Harmonics using analytical computation.	• Eliminate only the commutation torque ripple.

Table 6. Cont.

Method	Adapted Techniques	Advantages	Disadvantages
Current control-based technique	• Repetitive current control. • Predict current communication. • Eliminate negative DC.	• Low-cost drive strategy. • Smooth commutation.	• Commutation torque ripples. • Minimized torque ripple during low speed.
Phase conduction method	• Current overlapping method.	• Miniature motors used sensorless control for BLDC motors.	• Reducing the torque ripple components.
Model predictive control	• Estimation function using virtual vector delay time MPC–FCS.	• Good dynamic performance and robustness.	• Number of subsystem parts increases.
Direct torque control	• Torque estimation with control torque by a hysteresis controller. • Active-null vector modulation strategy.	• Structure very simple. • No coordinate transformations. • No PWM generation.	• Reduce low-frequency torque ripples.
FOC control	• Flux and current in the steady-state.	• An efficient control flux and torque.	• SVPWM complex to reduce torque ripple.
Model Adaptive control	• Fuzzy logic controller for speed control. • Reduction of torque ripples.	• The gain of the filter is adapted to reduce torque ripples.	• High sampling rate. • Maximum precision requires high computing power. • Increasing the cost of digital controllers.
Soft computing technique	• Neuro-fuzzy observer. • Artificial neural network (ANN).	• Minimize the torque ripples using soft computing techniques.	• Complex computational algorithm. • Real-time difficult.

4.1. Torque Ripple Techniques Explanation

Evaluating the sensitivity of control techniques to changing input parameters, such as switching frequency and PWM duty cycle, is critical for improving motor performance and guaranteeing consistent torque control. These characteristics have a considerable impact on the efficiency of various control approaches in regulating torque.

4.1.1. Sensitivity to Switching Frequency

Switching frequency is critical to the success of control techniques, such as DTC, FOC, and MPC.

4.1.2. Sensitivity to the PWM Duty Cycle

The PWM duty cycle directly impacts the voltage provided to the motor windings and, as a result, the production of torque.

Tables 7 and 8 present a comparison of the sensitivity of the PWM duty cycle and switching frequency to various control schemes (DTC, FOC, and MPC). While FOC necessitates accurate PWM control and has moderate sensitivity to switching frequency, DTC is extremely sensitive to switching frequency and is less impacted by the PWM duty cycle. MPC, on the other hand, exhibits reduced sensitivity to both, balancing computational demands and flexibility.

Table 7. Sensitivity of control strategies to switching frequencies [76–78].

Control Strategy	Sensitivity to Switching Frequency	Impact of High Switching Frequency	Impact of Low Switching Frequency	Trade-Offs
DTC	High	• Reduces torque ripple and improves response times. • Increases switching losses and thermal stress on inverter components.	• Results in higher torque ripple and slower dynamic response. • Less suitable for applications requiring precise torque control.	• Balances between reducing torque ripple and increasing thermal stress, potentially reducing efficiency and longevity.
FOC	Moderate	• Enhances smoothness of torque output and reduces current ripple. • Leads to increased switching losses and heating at very high frequencies.	• Less significant impact than DTC; still maintains reasonable control. • Lower risk of excessive losses compared to DTC.	• Moderate sensitivity allows for a balance between performance and efficiency, though it can still be affected by high losses.
MPC	Low	• Allows more frequent adjustments to control inputs, improving torque accuracy and reducing ripple. • Increases computational demands and switching losses.	• Minimal impact on torque accuracy due to predictive model optimization. • Retains robust control under varied conditions.	• Lower sensitivity makes it suitable for a wider range of applications, but high frequencies increase computational burden.

Table 8. Sensitivity of control strategies to the PWM duty cycle [79,80].

Control Strategy	Sensitivity to PWM Duty Cycle	Impact of High Switching Frequency	Trade-Offs
DTC	High	• DTC does not explicitly control the PWM duty cycle, but variations in supply voltage levels can affect stator flux and torque control. • Sensitivity is indirect and linked to input voltage fluctuations, potentially impacting torque control performance.	• Low sensitivity means less direct impact from duty cycle changes, but voltage variations can still affect performance indirectly.
FOC	Moderate	• PWM duty cycle directly influences the magnitude and direction of the current vector in the stator windings. • Incorrect PWM settings can cause poor current control, increased torque ripple, and reduced efficiency.	• High sensitivity requires precise PWM control to maintain optimal torque output and minimize ripple, balancing performance and efficiency.
MPC	Low	• MPC optimizes control actions based on predictive models rather than direct PWM duty cycle modulation. • Accurate modeling of duty cycle effects is crucial; incorrect predictions can degrade performance and torque control.	• Moderate sensitivity allows for flexibility in handling duty cycle variations, but requires accurate modeling to maintain effectiveness.

4.1.3. Comparison of Different Control Strategies

Table 9 compares three control systems for BLDC motors in electric vehicles (DTC, FOC, and MPC), focusing on their applications, recent improvements, recent advancements, and drawbacks. This comparison highlights the feasibility of each control approach for various EV applications, taking into account torque ripple, control complexity, and cost.

Table 9. A comparison of control techniques for BLDC motors in electric vehicles [12,13,29,31,61,68,71,72,81,82].

Control Strategy	Applications	Recent Advancements	Strengths	Drawbacks
DTC	• High-performance EV applications requiring rapid torque changes.	• Integration of advanced modulation techniques like SVM to reduce torque ripple and switching losses.	• Simple control structure. • Fast dynamic response. • Effective in reducing torque ripple under varying load conditions.	• High torque ripple and variable switching frequency. • Increased acoustic noise and reduced efficiency.
FOC	• EV applications needing smooth operation and low noise, such as passenger vehicles.	• Development of adaptive algorithms for real-time control parameter adjustments across diverse operating conditions.	• Smooth and efficient torque control with minimal ripple. • Compatible with sensorless techniques, reducing cost and enhancing reliability.	• Requires precise tuning and accurate knowledge of motor parameters. • Performance issues at very low speeds due to rotor position estimation challenges.
MPC	• High-precision EV applications and conditions needing control flexibility, such as advanced EV powertrains.	• Use of real-time optimization algorithms to lower computational requirements, enhancing feasibility for real-world applications.	• High precision and adaptability. • Dynamic torque ripple minimization. • Optimization of energy efficiency.	• Computational complexity. • High implementation cost due to real-time optimization algorithms.

The table discusses the distinct advantages and problems of DTC, FOC, and MPC control techniques for BLDC motors in EVs, emphasizing their specialized applications and recent improvements. DTC has a fast dynamic response but suffers from significant torque ripple, making it excellent for applications that need quick torque changes but less optimal for precise jobs [29,61,68]. FOC provides smooth torque control and minimum ripple, making it ideal for low-noise applications; nevertheless, careful tuning is required, especially at low speeds [12,13,72,75]. MPC is distinguished by its flexibility and minimal torque ripple despite the fact that it requires significant processing resources and expenditures, making it best suited for sophisticated applications demanding precise control and adaptability [31,81,82].

5. Mechanical Concepts for Torque Ripple Prevention

5.1. Techniques

Multiple sophisticated modulation techniques are used to reduce these causes of torque ripple by optimizing the motor's current and voltage control:

5.1.1. SVPWM Techniques

This approach optimizes the switching sequences to provide a more sinusoidal current waveform, decreasing torque ripple and harmonic distortion in the motor's output. SVPWM modifies the voltage vectors dynamically to match the required torque output [83].

5.1.2. Adaptive HCC

This approach optimizes the switching sequences to provide a more sinusoidal current waveform, decreasing torque ripple and harmonic distortion in the motor's output. SVPWM modifies the voltage vectors dynamically to match the required torque output [84].

5.1.3. Dynamic FOC Techniques

FOC decreases torque ripple by isolating the torque- and flux-producing components of the current, allowing for more accurate torque control. The dynamic version constantly reacts to variations in load and speed, ensuring optimal performance and minimizing torque ripple under changing conditions [85].

5.1.4. Finite Control Set MPC (FCS-MPC)

This sophisticated control approach uses a mathematical model to forecast future motor behavior and picks optimal control actions to minimize a cost function based on torque ripple and energy usage by improving the efficiency of BLDC motors in real-time applications [86].

As seen in Figure 7, these methods provide strong, constant static and dynamic efficiency in order to lessen the ripple impact of torque. According to the survey, in-wheel BLDC motors produce less torque ripple and are appropriate for low-power electric vehicles.

One of the primary causes of the overall torque ripple that adversely impacts the motor's performance is cogging torque. PM flux has a tendency to pass via stator teeth because it always chooses the route with the least amount of resistance, which causes an undesired torque to be generated [87]. Three main ways are currently available to weaken cogging torque: structural parameter optimization approaches, rotor innovation, and stator innovation. In order to reduce the cogging torque for PM machines, a dynamic reduction technique based on HTC is proposed. This technique is applied to a fractional slot PM machine (6-slot/4-pole), resulting in a weakening ratio of 96.4% and a cogging torque reduction from 1.23 N·m. to 44.21 mN·m., with a weakening ratio of 94.0%, on an integer slot PM 6-slot/2-pole synchronous machine. The author of [88] offered a comprehensive description of the dynamic weakening process of the cogging torque.

The saliency-based sensorless-controlled IPMSM with a focused winding design approach was proposed by the author of [89]. First, the electromagnetic characteristics are derived using mathematical approaches for sensorless controllability evaluation. These parameters are the THD of the phase inductance and the waveforms of the self-inductance and mutual inductance along the d- and q-axes.

According to the author of [90], when the motor is operating at a very low velocity, a normal PI controller is insufficient to eliminate the acceleration ripple because vehicle inertia decreases the speed controller bandwidth. It has been demonstrated that using a resonance controller in conjunction with a PI controller may lower the vehicle's speed ripple by 83% when compared to using a traditional PI controller. Also, because the PI controller's noise cancelation capacity has decreased, raising the bandwidth may make the entire system unstable. Due to the increased total design flexibility, the removal of torque ripple at the source through the use of an active control approach will reduce speed ripple or vibration and encourage the use of PM machines in a wider variety of applications.

The authors of [91] expected an optimization of the diffusion harmonics if the slots were placed on the rotor's surface, but that the air-gap flux density's harmonic content would rise, according to the analytical formula for cogging torque and the finite element simulation. In this instance, even if the auxiliary slots lessen the cogging torque, the air-gap flux density's harmonic content increases, aggravating the output torque ripple. Using inwardly biased slots, outwardly biased slots, and symmetrical auxiliary slots may lower the cogging torque by 75.64%, 57.53%, and 75.88%, respectively. A higher cogging torque may be obtained by symmetric auxiliary slots and inwardly biased slots than by outwardly biased slots. Therefore, to maximize the motor's cogging torque, symmetric auxiliary slots and inwardly biased slots are employed.

A straightforward EMPSC control mechanism was suggested by the author of [92] to enhance PMSM performance with torque ripple reduction. With significant enhancements in performance, such as the elimination of speed drift, a noteworthy 39% lowering of torque ripple, and an astounding 28% reduction in current deformation in comparison to

the traditional FOC method, the simulation and experimental results validate the viability of the suggested control method. Moreover, a 50% decrease in speed fluctuation was used to confirm robustness against outside influences. The PMSM is anticipated to operate at 2000 rpm in the simulation research that follows, with an external load torque of 0.1 Nm applied between 7 and 9 s.

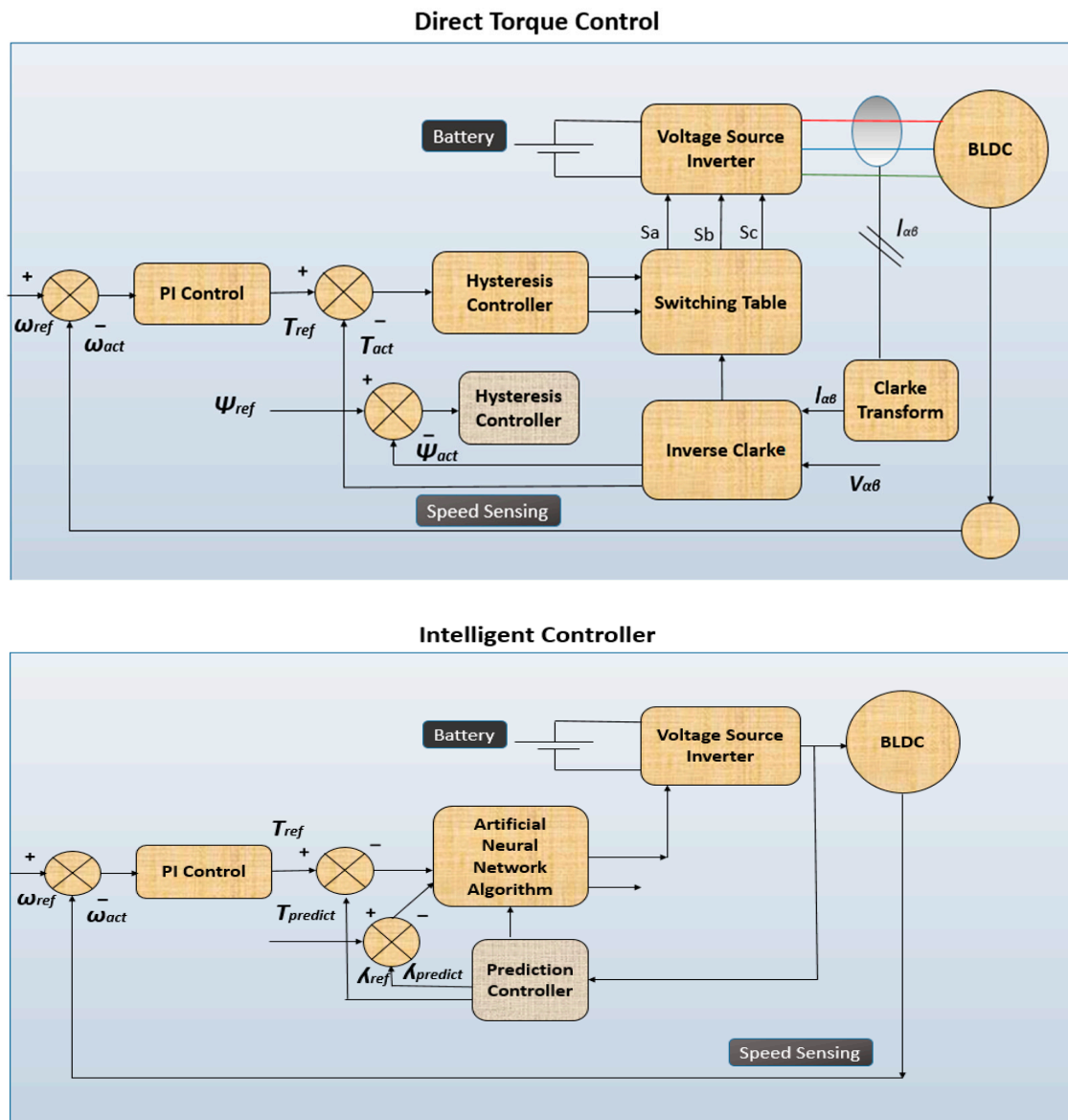


Figure 7. For BLDC, control methods include DTC and IC [87–89,91,92].

The study in [93] proposed a disturbance observer-based control scheme for the PMSM prototype kit. For both loops, a discrete-time PI–PI control system with cascade structure and tracking anti-windup mechanism was employed. The precise motion equation of the PMSM was derived as the exact projection of the mechanical speed as the foundation for the total disturbance estimate using HODO. Friction, hysteresis, and torque losses from drag arising from the time-varying flux are all included in the motion equation of the proposed HODO. Hysteresis current control (HCC) maintains the current within a certain range, effectively reducing torque ripple [75]. It has been proven that this can enhance the PMSM system’s speed-tracking performance in the presence of external disturbances and unmodeled dynamics related to cogging torque and high-frequency electromagnetic noise. The speed controller makes up for the predicted overall disturbance. To properly evaluate

the torque ripple reduction achieved by different control systems for BLDC motors, precise numerical data representing both simulation findings and empirical (real-world) test results are included, as shown in Table 10 [94].

Table 10. Comparing simulation findings and empirical data for torque ripple elimination [94].

Operational Condition	Control Strategy	Simulation Results (Torque Ripple % Reduction)	Empirical Results (Torque Ripple % Reduction)
Low Speed, Low Load (500 RPM)	PWM	12%	11.8%
	FOC	6%	6.2%
	HCC	5%	5.1%
	MPC	4%	4.3%
Medium Speed, Medium Load (2000 RPM)	PWM	15%	14.7%
	FOC	10%	9.8%
	HCC	9%	8.7%
	MPC	7%	7.2%
High Speed, High Load (5000 RPM)	PWM	18%	17.5%
	FOC	12%	12.1%
	HCC	10%	10.3%
	MPC	7%	6.9%

The comparison of simulated and actual data in Table 10 reveals a good connection, with slight differences only. These variances, such as the modest discrepancy in torque ripple reduction between PWM and MPC at high speeds, can be attributed to changes in real-world testing settings and probable measurement mistakes.

The comparative graph in Figure 8 plots torque ripple percentages against motor speed for various control strategies, such as PWM, FOC, HCC, and MPC. These curves provide a clear visualization of the performance differences across different speeds [95].

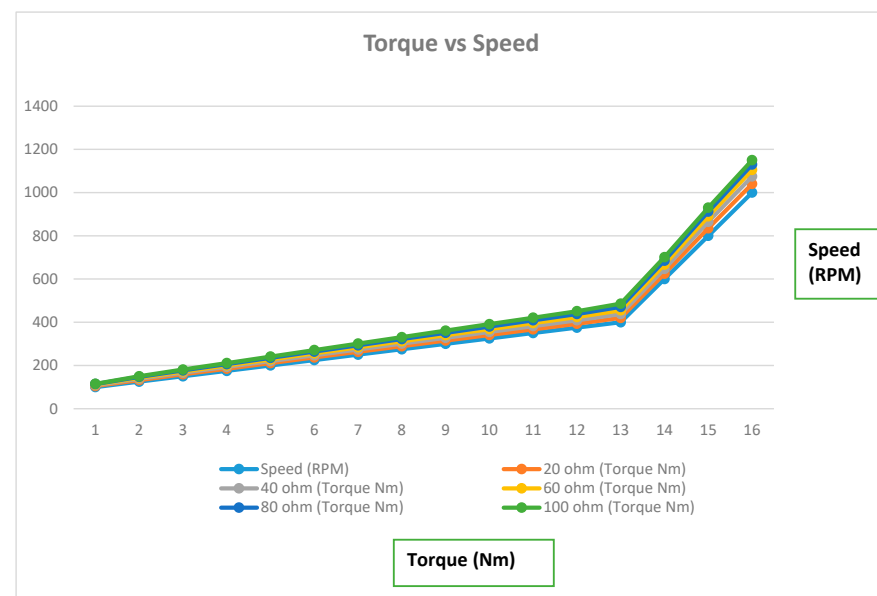


Figure 8. Comparison of torque ripple reduction for different control strategies at different motor speeds [95].

6. Impact of Temperature

6.1. Effect of Temperature on Torque Performance

6.1.1. Resistance Changes

As the temperature rises, the motor windings' resistance also rises. This causes higher I^2R losses (Joule heating), which lowers the motor's overall efficiency and torque production. Torque may decrease as a result of this action, particularly when a heavy load is applied continuously [96].

6.1.2. Magnetic Flux Reduction

Permanent magnets used in BLDC motors may experience a drop in magnetic flux density as a result of higher temperatures. Because the motor can no longer provide as much force, the torque output may be reduced as a result of this decrease in magnetic strength [97].

6.1.3. Increased Eddy Currents and Hysteresis Losses

Elevated temperatures can lead to increased core losses in magnetic materials because of hysteresis and eddy currents. This can further impair torque performance by lowering the effective power output [96,97].

6.2. Major Parameters Affected by Temperature

During motor operation, temperature increases affect a number of critical parameters, which are described below.

6.2.1. Winding Resistance

As a motor's temperature rises, so does its electrical resistance, which lowers efficiency and raises losses. Temperature-dependent resistance models, which modify the winding resistance in response to the motor's anticipated thermal state, were used in our simulations to simulate this effect [98].

6.2.2. Magnetic Flux Density

As temperatures rise, the permanent magnets used in motors may experience a reduction in magnetic flux density, which might have an impact on torque output and overall motor performance. To adequately depict this behavior, we used temperature-dependent demagnetization curves in our simulations [99].

6.2.3. Thermal Feedback and Modifications to the Control Strategy

A thermal feedback loop in the control techniques is included in the study to guarantee the accuracy of the simulation findings. In response to the simulation-predicted real-time thermal conditions, this feedback loop modified the control settings. To account for temperature fluctuations in real-time optimization, the MPC method was changed [100]. This modification took into consideration the impacts of temperature on the electrical characteristics of the motor.

6.3. Integration of Thermal Effects in Simulation Models

The simulation findings were integrated with thermal effects by the utilization of a linked electromagnetic-thermal model. With the help of this method, it was possible to model the motor's electrical behavior and thermal dynamics at the same time, leading to a thorough grasp of how temperature affects motor performance over time. The thermal model simulated heat dissipation by taking into account several cooling methods, such as conduction, convection, and radiation, in addition to accounting for heat produced by electrical losses like copper and iron losses [99,101].

6.4. Mitigation Strategy

There is a discernible decrease in torque output, especially in high-temperature conditions, as a result of higher resistance and decreased magnetic flux. Constant exposure to high temperatures can shorten the lifespan and dependability of motors by hastening the aging of permanent magnets and insulating materials (accelerated aging). In severe situations, the heating effect may result in thermal runaway, a condition in which the motor produces more heat than it is able to release, potentially leading to failure [102]. To reduce the impacts of temperature on torque performance, numerous solutions can be used, as described here.

6.4.1. Enhanced Cooling Systems

Using advanced cooling techniques like liquid cooling or forced air cooling can assist in maintaining ideal operating temperatures. Liquid cooling, in particular, is beneficial in high-performance applications that require higher heat dissipation [103].

6.4.2. High-Temperature Materials

Using materials with better thermal tolerances for windings, magnets, and insulation can help mitigate the detrimental effects of temperature rises. For example, samarium–cobalt magnets are less susceptible to demagnetization at high temperatures than neodymium magnets [104].

6.4.3. Thermal Modeling and Predictive Control

Integrating thermal models into motor control algorithms enables real-time predictive changes to reduce the influence of temperature fluctuations. Predictive control can optimize the motor's operational settings such that torque performance remains within acceptable ranges despite temperature variations [103,104].

6.4.4. Temperature Monitoring and Feedback Systems

The motor control unit includes real-time temperature sensors and feedback systems that may dynamically modify operational settings to prevent overheating and to decrease thermal stress on components [103,105].

7. Limitations

The control systems used to regulate torque and speed, such as FOC, MPC, and DTC, have a considerable impact on the performance and efficiency of BLDC motors. Each technique has unique advantages and disadvantages, and may be used in different situations. A brief comparison of the different control strategies is given in the accompanying Table 11, which also highlights the main benefits, disadvantages, and trade-offs of each.

Table 11. A comparison of DTC, MPC, and FOC for torque control in BLDC motors [76,106,107].

Control Strategy	Strengths	Limitations	Trade-Offs
DTC	Fast dynamic response due to direct control of torque and flux.	- High torque ripple, especially at low speeds. - Variable switching frequency, leading to increased switching losses and EMI.	Ideal for applications needing rapid torque adjustments but less suitable where smooth torque and low noise are critical.

Table 11. Cont.

Control Strategy	Strengths	Limitations	Trade-Offs
MPC	• High flexibility and precision in torque and speed control. • Effective in minimizing torque ripple and energy consumption.	• Computationally intensive, requiring high processing power. • High implementation cost due to complex algorithms and hardware requirements.	• Best for dynamic conditions needing low torque ripple and efficiency, but limited by high computational and cost demands in simpler applications.
MPC	• Provides smooth and efficient torque control across a wide range of speeds. • Low torque ripple and high performance.	• Requires precise tuning of control parameters, which can be complex. • Less effective at very low speeds due to rotor position estimation errors.	• Suitable for applications requiring low noise and smooth operation, but the complexity of tuning and low-speed performance may limit some uses.

DTC is known for its quick dynamic response due to direct torque and flux control, but it has significant torque ripple and a variable switching frequency, which can contribute to increased noise and losses, making it unsuitable for precision applications [106]. MPC provides great accuracy and flexibility in torque control and ripple minimization, but its computational complexity and high implementation cost might be prohibitive, particularly in cost-sensitive or simpler systems [107]. FOC excels at delivering smooth and efficient torque control with minimum ripple, making it excellent for applications where low noise and smooth operation are critical. However, it requires accurate tuning and may struggle with torque control at extremely low speeds, owing to estimating flaws [76]. Table 11 shows that while DTC is useful for applications requiring quick torque changes, MPC is better suited for circumstances demanding minimal torque ripple and efficiency, despite its greater cost. In contrast, FOC is best suited for low-noise applications, but it requires careful tuning and may not operate well at low speeds. This comparison analysis emphasizes the necessity of selecting the best control approach for the application and operating environment.

Electric motor performance diminishes over time owing to a variety of causes, including thermal stress, mechanical wear, and electromagnetic fatigue, all of which can have a substantial influence on efficiency and dependability. Understanding these degradation pathways is critical for establishing effective mitigation techniques that increase motor lifetime. Table 12 below summarizes the significant degradation variables influencing motor performance and offers techniques for mitigating their impact [54,77,104,108].

Table 12. Motor performance degradation factors and mitigation strategies [54,77,104,108].

Degradation Factor	Description	Mitigation Strategies
Thermal Stress	High temperatures increase winding resistance and reduce magnet coercivity, decreasing torque and efficiency.	• Implement advanced cooling systems (e.g., liquid cooling, forced air). • Use high-temperature insulation materials.

Table 12. Cont.

Degradation Factor	Description	Mitigation Strategies
Mechanical Wear	Friction in bearings and moving parts leads to increased noise, vibration, and eventual failure.	• Utilize high-quality materials (e.g., ceramic bearings). • Apply predictive maintenance techniques (e.g., vibration analysis).
Electromagnetic Fatigue	Repetitive electromagnetic stress reduces the magnetic performance of rotor and stator core materials.	• Optimize control strategies (e.g., MPC for real-time adjustments). • Monitor motor condition and adjust operating parameters accordingly.
Insulation Breakdown	Thermal cycling and high voltages degrade insulation, increasing the risk of short circuits.	• Enhance insulation materials to withstand higher temperatures and electrical stresses. • Employ thermal imaging for early detection of insulation degradation.
Aging of Permanent Magnets	Exposure to high temperatures and mechanical stress reduces the magnetic flux density over time.	• Use magnets with higher thermal stability (e.g., samarium–cobalt). • Implement temperature monitoring to prevent excessive heat exposure.

Table 12 identifies a number of important variables, including thermal stress, mechanical wear, electromagnetic fatigue, insulation failure, and permanent magnet aging, which eventually lead to a decline in motor performance. Each component, such as increased resistance, noise, vibration, and decreased magnetic flux density, is associated with particular consequences for motor dependability and efficiency [54,77]. High-quality materials and sophisticated cooling systems are advised to control mechanical and thermal stress in order to lessen these impacts. Vibration analysis and thermal imaging are two predictive maintenance approaches that can identify wear indicators early and stop breakdowns. Model predictive control (MPC) is one example of an optimized control strategy that can lessen electromagnetic stress and adjust to changing motor conditions. Electric motors' long-term performance and dependability may be greatly improved by putting these mitigation techniques into practice and guaranteeing their efficient functioning in a variety of applications [104,108].

Three control strategies—DTC, FOC, and MPC—are thoroughly compared in Table 13, with an emphasis on the advantages, difficulties, real-world uses, and metrics for assessing the torque ripple reduction of each approach. This comparison aids in determining which control method is best for a certain application, taking into account performance standards and operational needs.

The benefits, drawbacks, and real-world uses of each control approach (DTC, FOC, and MPC) for reducing torque ripple in electric motors are highlighted in Table 13. DTC is best suited for applications that value quick torque adjustments above smooth operation because it provides a fast dynamic response, but it is hampered by high torque ripple and significant switching losses. While MPC offers high precision and adaptability with lower torque ripple but requires significant computational resources, making it best suited for advanced, high-precision applications, FOC offers smooth torque control with minimal ripple, making it suitable for precision applications, although it requires precise tuning [79,80,104–106,109].

Table 13. Analysis of torque ripple reduction control strategies (DTC, FOC, and MPC) [79,80,104–106,109].

Control Strategy	Benefits	Challenges	Practical Applications	Metrics for Evaluating Effectiveness
DTC	• Fast dynamic response due to direct control of torque and flux.	• High torque ripple, especially at low speeds. • Increased switching losses and thermal stress on inverter components.	• Traction control systems in EVs. • Industrial drives with rapid acceleration and deceleration needs.	• TRR Measures variation in torque output relative to the average torque.
FOC	• Smooth torque control through decoupling of stator current components.	• Requires precise tuning of PI controllers. • Reduced accuracy at very low speeds due to rotor position estimation errors.	• Precision robotics. • Conveyor systems. • Electric power steering in vehicles.	• CHD Assesses distortion in the current waveform affecting torque smoothness.
MPC	• High precision and flexibility with predictive model optimization. • Effective in minimizing torque ripple and improving efficiency.	• Computationally intensive. • High implementation cost due to advanced hardware and algorithms.	• Advanced EV powertrains. • Wind turbines. • Aerospace actuators requiring high control precision.	• RMSE of torque evaluates deviation of actual torque from the reference torque.

8. Future Scopes

We have found many significant holes in the existing research landscape that must be addressed. These include developing more adaptive control techniques capable of dynamically responding to real-time changes in motor conditions to improve EV dependability and efficiency [110,111]. Furthermore, more improved sensor technologies with real-time feedback on motor parameters are required to optimize control techniques [96]. There are four categories of EVs: HEV, PHEV, BEV, and FCEV. These EVs are all in style right now. The primary obstacles to BEV and PHEV adoption in the future market are the absence of energy storage devices and charging facilities. In military and utility vehicles, research on fuel cell electric vehicles (FCEVs) using affordable fuel cells is particularly popular. While FOC, DTC, and MPC have demonstrated their efficacy in controlling torque, future research could concentrate on creating adaptive control strategies that dynamically adapt to changing driving conditions and motor states. By using machine learning algorithms to forecast the best course of action for control based on real-time data, these adaptive systems may be able to improve torque management's responsiveness and efficiency [110]. Research might look at combining modern sensor technologies, such as fiber optic sensors or MEMS-based devices, to offer real-time input on motor characteristics. These sensors might improve torque control accuracy by providing exact data on characteristics like temperature, magnetic flux, and vibration [111].

Future studies might look into hybrid control systems that combine the advantages of several control methods, for example, by combining DTC's quick reaction with MPC's accuracy. These hybrid systems might improve performance by dynamically altering the

control strategy depending on real-time conditions and maximizing torque production while lowering energy usage [112]. Implementing AI and deep learning models in torque control systems might considerably improve predictive capabilities. These models might learn from large datasets of driving behaviors and motor performance, allowing them to predict changes in torque demand and alter control tactics in advance [113]. Another interesting path is the use of AI and machine learning to create adaptive torque management systems that predict appropriate control actions based on real-time data, improving responsiveness and energy efficiency [113]. Quantum algorithms might perform complicated computations at unprecedented rates, enabling near-instantaneous modifications to control inputs based on real-time motor data, resulting in optimal torque control and energy efficiency [81]. Quantum computing has the potential to make quick, real-time modifications to control inputs, which might considerably improve torque control and energy efficiency in next-generation EVs [99]. Furthermore, the use of biologically inspired control algorithms, such as neural networks modeled after animal movement, can increase the resilience and flexibility of torque control systems in the face of variable driving situations [82]. Future studies might potentially look at biologically inspired control algorithms, such as neural networks based on animal movement, to improve the flexibility and robustness of torque control systems. These algorithms may give reliable performance even under uncertain driving situations or in the presence of malfunctions [82]. Any drive wheel can have the vehicle application motor's drive duty cycle. There are several benefits to having an engine behind the steering wheel of the car. The primary focus of this research is on control methods and internal wheel motor design. In EVs, many motor types are utilized, including BLDC, PMSM, IM, SRM, and SynRM. Future studies on each of the four motors will improve their shortcomings. The benefits of two distinct motors, one accounting for reluctance torque and the other for permanent magnets, are combined to create the current trend in e-motors. Tricycles and other low-power vehicles can benefit from the BLDC motor for EVs. The torque and rating of the machine are directly impacted by the flux density magnitude due to the PM internal rotor BLDC. The second drawback is that trapezoidal winding distribution in the air gap generates greater heat and losses when thermally withstood at driving temperature conditions. In EVs, the torque ripple is greater because of the harmonic content of the BLDC system's back EMF. When the speed of an EV is altered, the magnetic depolarization effect limits the BLDC input voltage. To solve these problems, research on flux-condensing PM is still being conducted.

9. Conclusions

These days, electrically powered cars are a great necessity for automobile travel because of the increasing contaminants in the environment, as well as rising fuel prices. The primary causes of the sharp rise in gasoline prices include the rising price of petroleum products in the global marketplace, high sales taxes, and the limited supply of combustible fossil fuels. The following is a critical assessment of the motor selection process and control strategies for EV design in order to minimize torque ripple:

PMBLDC is an expensive rare earth material that has issues with dependability and torque disturbances. It may be made better by utilizing DTC and MPC control approaches, which enhance high-speed efficiency, reduce torque ripple, use inexpensive iron, and boost BLDC dependability for the next EVs. When compared to alternative solutions, such as predictive, adaptive, non-linear control techniques, and the PI–PI control system, the EMPSC control mechanism for in-wheel BLDC motor driving reduces the torque fluctuation.

These important elements, along with a number of other considerations, including affordability, light weight, high electrical power density, excellent torque density, maximal velocity, high efficiency, ease of use, and extended lifespan, might be taken into account when designing future electric vehicles.

Author Contributions: Conceptualization, A.A.T.; methodology, A.A.T.; software, A.A.T.; validation, M.I.M. and H.M.C.; formal analysis, A.A.T.; investigation, A.A.T.; resources, H.M.C.; data curation,

A.A.T.; writing—original draft preparation, A.A.T.; writing—review and editing, A.A.T., H.M.C., and M.I.M.; visualization, A.A.T.; supervision, H.M.C.; project administration, H.M.C.; funding acquisition, H.M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF), funded by the Korean government (NRF-2022H1A7A2A02000033).

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

EV	Electric Vehicle
DTC	Direct Torque Control
FOC	Field Orientation Control
SMC	Sliding Mode Control
IC	Intelligent Control
MPC	Model Predictive Control
BLDC	Brushless Direct Current Motor
EM	Electromagnetic
CO ₂	Carbon Dioxide
PEC	Power Electronic Converters
ICEV	Internal Combustion Engine Vehicles
EMI	Electromagnetic Interference
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
IM	Induction Motor
SRM	Switched Reluctance Motor
SynRM	Synchronous Reluctance Motor
PLL	Phase-Locked Loop
HEV	Hybrid Electric Vehicle
BEV	Battery Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicles
FCEV	Fuel Cell Electric Vehicles
NdFeB	Neodymium Iron Boron
EMF	Electro Magnetic Field
PWM	Pulse Width Modulation
SVPWM	Space Vector PWM
DC	Direct Current
IPMSM	Interior Permanent-Magnet Synchronous Motor
RSM	Response Surface Methodology
FEA	Finite-Element Analysis
HCC	Hysteresis Current Control
TRR	Torque Ripple Ratio
CHD	Current Harmonic Distortion
RMSE	Root Mean Square Error

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