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Critical Aspects of Electric Motor Drive Controllers and Mitigation of Torque Ripple - Review

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ABSTRACT Electric vehicles (EVs) are playing a vital role in sustainable transportation. It is estimated that by 2030, Battery EVs will become mainstream for passenger car transportation. Even though EVs are gaining interest in sustainable transportation, the future of EV power transmission is facing vital concerns and open research challenges. Considering the case of torque ripple mitigation and improved reliability control techniques in motors, many motor drive control algorithms fail to provide efficient control. To efficiently address this issue, control techniques such as Field Orientation Control (FOC), Direct Torque Control (DTC), Model Predictive Control (MPC), Sliding Mode Control (SMC), and Intelligent Control (IC) techniques are used in the motor drive control algorithms. This literature survey exclusively compares the various advanced control techniques for conventionally used EV motors such as Permanent Magnet Synchronous Motor (PMSM), Brushless Direct Current Motor (BLDC), Switched Reluctance Motor (SRM), and Induction Motors (IM). Furthermore, this paper discusses the EV-motors history, types of EV-motors, EV-motor drives powertrain mathematical modelling, and design procedure of EV-motors. The hardware results have also been compared with different control techniques for BLDC and SRM hub motors. Future direction towards the design of EV by critical selection of motors and their control techniques to minimize the torque ripple and other research opportunities to enhance the performance of EVs are also presented.

INDEX TERMS Electric vehicles, Electric motors, Control techniques, Torque ripple, Brushless DC motor, Permanent magnet synchronous motor, Induction motor, Switched reluctance motor, Hub motors, e-motors design.

ABBREVIATION

ANN	Artificial Neural Network	IWM	In-Wheel Motor
ASD	Adjustable Speed Drives	NNC	Neural Network Control
BEMF	Back Electro-Motive Force	MPC	Model Predictive Control
BLDC	Brushless DC Motor	MPCC	Model Predictive Current Control
DTC	Direct Torque Control	MPTC	Model Predictive Torque Control
DITC	Direct Instantaneous Torque Control	NdFeB	Neodymium Iron Boron
EEC	Electric Equivalent Circuit	PMSM	Permanent Magnet Synchronous Motor
EMF	Electro Magnetic Field	PID	Proportional Integral Derivative
EMI	Electromagnetic Interference	PM	Permanent Magnet
EM	Electro Magnetic	PSO	Particle Swarm Optimization
EVs	Electric Vehicles	PI	Proportional Integral
FEA	Finite Element Analysis	PWM	Pulse Width Modulation
FLC	Fuzzy logic Control	SRM	Switched Reluctance Motor
FOC	Field Oriented Control	SMC	Sliding Mode Control
FTC	Fault Tolerant Control	SynRM	Synchronous Reluctance Motor
ICE	Internal Combustion Engine	TSF	Torque sharing Function
IM	Induction Motor	T/I	Torque/Current Ratio

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I. INTRODUCTION

A. Background

Since the lase decade, environmental pollution has increased severely owing to greenhouse gases, leads such as carbon dioxide, nitrous oxide, methane, oxides of nitrogen, sulphur dioxide, hydrocarbon. Due to higher demand for fuel, prices are increasing day by day it becomes most expensive. In [1-4] vehicle engine is one of the most significant sources of greenhouse gas emissions, accounting for 30% to 50% of road CO_2 emissions. Vehicle emission increases in the world because of the growing population, economic development, which lead are showing in usage of vehicles and urbanization. In [5-7] most countries in the world have started to pay attention and willingness towards minimizing the earth's atmospheric gas emissions and to improve the air quality in all the locations. In [8] compared to automobiles powered by Internal Combustion Engine Vehicles (ICEVs), EVs have zero emissions and are more effective with huge promise for reducing CO_2 gas emissions when integrated with a less carbon power sector as shown in Fig. 1. In this case, many countries have stated that they want to achieve 100% Zero-Emission Vehicles. However, [9, 10] predicted that by 2023 there will be 10.2 billion EVs in the market, accounting for around 1.5% of the global inventor. Therefore, EVs adoption still has a long way to go.

The invention and development of EVs in the last 150 years has come a long way. The development of EVs from a simple non-chargeable state to modern control techniques can be categorized into three stages: early stage, middle stage, and present stage as shown in Fig. 2 [11,12].

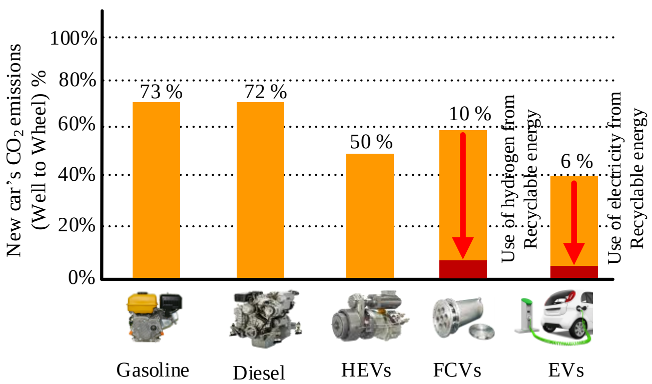

Figure 1. Transportation vehicle CO_2 emission levels

B. Motivation of Research

In [13], e-motor technique has a set of their own benefits and drawbacks for driving a powertrain over a long period of development. During the last ten decades, much automotive industry started to change its motor structure and control techniques to improve EVs performance. In [14] majority of EV motors are using rare earth magnet material high cost, the main advantage which are of BLDC motor is high torque density and power density. In [15,16] main issues in BLDC conventional and in-wheel motors are torque ripple, fault-tolerant capability, EMI, acoustic noise, control problem in field weakening ability, and high cost of PM materials. This review discusses mitigating the problem over design and different control techniques aspects. In [17, 18], the author discussed PMSM to meet the desired EV characteristics, high torque and power density. The main issue is high-cost PM rare earth material neodymium. Mitigate this problem, low-cost ferrite is suitable, but it has low energy and coercivity. In [19, 20] new topology PM assisted, spoke, axial and In-wheel motors are proposed as the performance. This review discusses low-cost PMSM material and PM topology. In [21, 22, 23] non-magnet low-cost induction motor, both stator and rotor material losses are high which decreases the efficiency and fault tolerance. Which are the main drawback of this EV drive system. This review mitigates the technique of IM reducing losses and improving efficiency.

In [24], it is stated that Double salient switched reluctance both in-wheel and inner rotor aligned with minimum reluctance non-magnet material is suitable for EV drive with simple construction, robustness, high power density, long constant power range, and enhanced reliability for fault-tolerant capability. In [25] the main problems identified are: controllability, torque density, torque ripple, vibration, and acoustic noise and fault diagnosis. This review article discusses the design and control techniques aspects to mitigate the SRM torque ripple, vibration, torque density, acoustic noise and fault tolerance. Article [26] dealt that, other motors were also suitable for EV drive systems like synchronous reluctance motor (SynRM) having the good fault-tolerant capability, robust, high efficiency, and compact size. In [26, 27] the main problem addressed were the controllability, power density, and power factor of the reluctance motor.

Control techniques are adopted to improve the reliability, control of fault-tolerant, electromagnetic interference, acoustic noise, vibration and torque ripple mitigation. The most promising motor among EVs are listed in Table I that are particularly important to explore by its most popular control schemes.

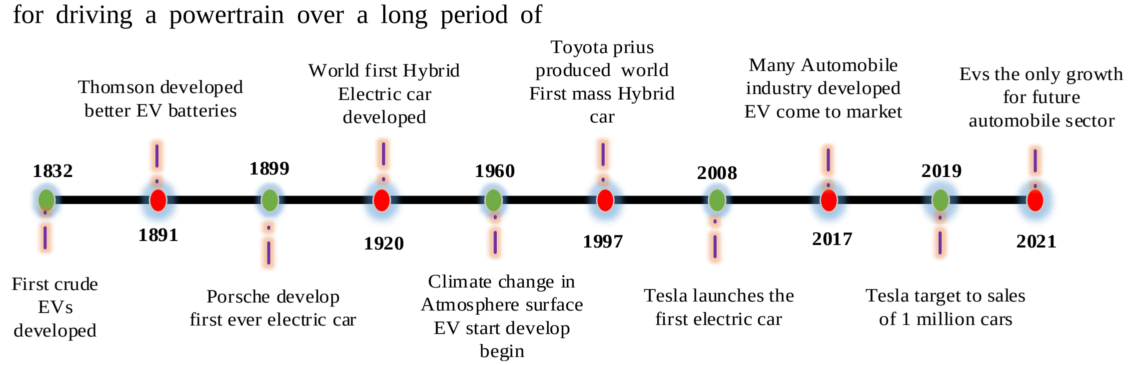

Figure 2. EV Generation Growth [30, 31]

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TABLE I Comprehensive and concise literature survey on EV motors

EV motors	Key challenges	Control techniques	Design topology	Ref
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 arc width position, interior rotor (surface mounted, buried, inserted in-wheel motor.	[15,16]
PMSM	High-cost magnet (Neodymium, samarium), demagnetization, torque ripple, fault tolerant.	Low-cost ferrite material, FOC, DTC-SVM, MPC-PTC, SMC, intelligent controller, and sensor less controller.	PMAsynRM, PM Axial flux motor, PM spoke type motor.	[17-20]
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, modelling skewed rotor.	[21-23]
SRM	Less torque density, high acoustic noise and vibration, high torque ripple.	TSF, DTC, DITC, MPC, FOC, MPC, SMC, and intelligent controller.	Increasing stator and rotor poles, axial flux SRM, optimize stator/rotor pole arc and length.	[24,25]

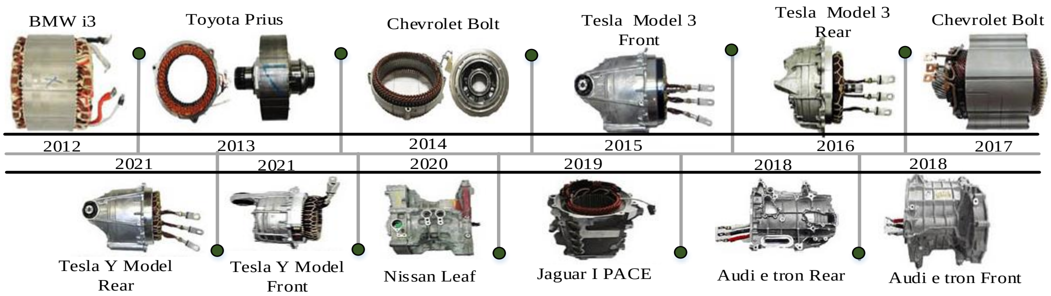

Figure 3. E-motor development in the last decade

The most traditional control schemes such as: field-oriented control, direct torque control, model predictive control, sliding mode control and intelligent control are adopted in EV motors both in-wheel drive and indirect drive wheel. Fig.3 shows their development in the last decade.

Article [28] considered Direct torque control (DTC) which provides a better dynamic response resulted as the main advantage of the DTC algorithm and it has a simple structure for conventional and in-wheel motors. DTC is preferred for high dynamic applications, but it creates a high current and torque ripple. Article [29] proposed Field Oriented Control (FOC) to provide good steady-state behavior over the full load torque and speed ranges. The inductance distribution in the rotor position uses an effective real-time inductance measurement method to minimize torque ripple and achieve better steady-state performance. Article [30] proposed a novel finite-set Phase-Locked Loop (PLL) sensorless scheme combined with duty-cycle Model Predictive Control (MPC) for in-wheel motors, which improves the dynamic performance and robustness of the system. Article [31] proposed a finite set MPC that combines virtual vector and duty cycle to improve steady-state and dynamic performance without the need for a modulator. Article [32] considered the fault-tolerant scheme of the in-wheel motor after failure and proposed an MPC fault-tolerant scheme based on virtual vector, which avoids the complex controller topology reset in the traditional scheme and has good fault-tolerant performance.

Article [33] considered a Sliding Mode Controller (SMC) as a robust non-linear system, dynamics of a nonlinear system by the application of high switching control. Combined adaptive integral higher-order SMC is used to reduce the chattering problems which can eliminate external disturbances. Article [34] proposed the speed and torque responses, advanced fault-tolerant control of induction motor, high-performance EV/HEV applications based on modern and intelligent controllers. In [35] the development of sensor- less or model-based control for full speed range using effective rotor position estimation function for traction motor application was proposed.

The significant contribution in this paper is as follows:

- A brief history of types of EVs and their motor categories are discussed in detail with diagrams.
- A comprehensive review of BLDC, PMSM, IM and SRM advanced control techniques such as FOC, DTC, MPC, SMC, Intelligent controller and torque ripple mitigation are discussed.
- The BLDC and SRM hub motor with advanced control techniques were discussed in detail.
- The fundamental theory behind motor designing and its steps are illustrated with a flow diagram.
- The open challenges and future research opportunities are discussed.

Fig.4. represents the flow and survey organization of the presented paper. In the next section, the types of EVs and electric motor used in EVs are discussed.

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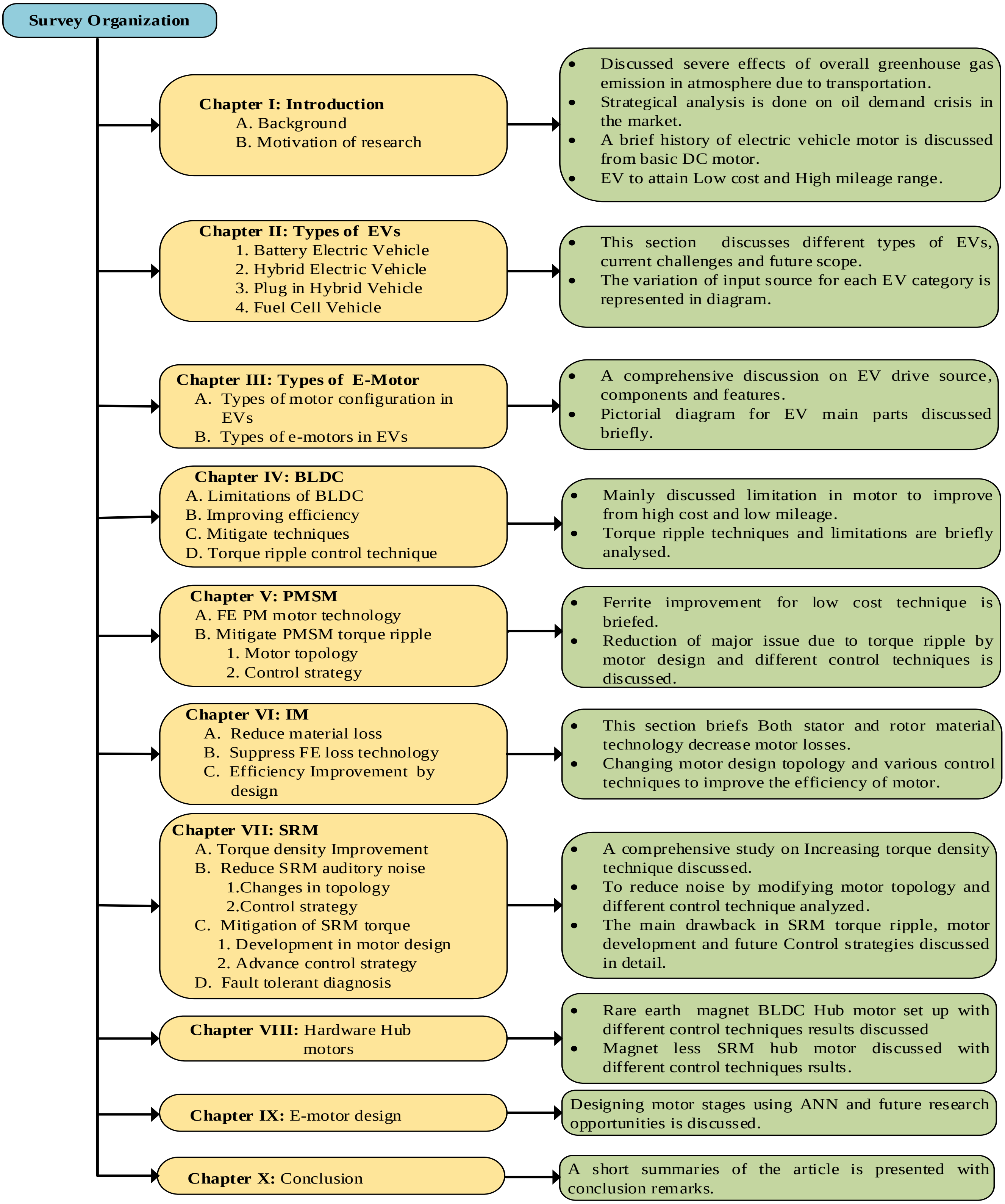

Figure 4. Organization of the review article

II. Types of Electric Vehicles

In [36, 37] presented those batteries are the only source of power for Battery Electric Vehicles (BEVs). They have zero emissions since they use an electric motor to turn the wheels.

In [36] stated that Plug-in Hybrid EV (PHEV) have a range of 20 to 30 miles of zero-emission driving and can also run-on gasoline or diesel for longer excursions. To maximize their zero-emission capability, they must be connected to a power supply.

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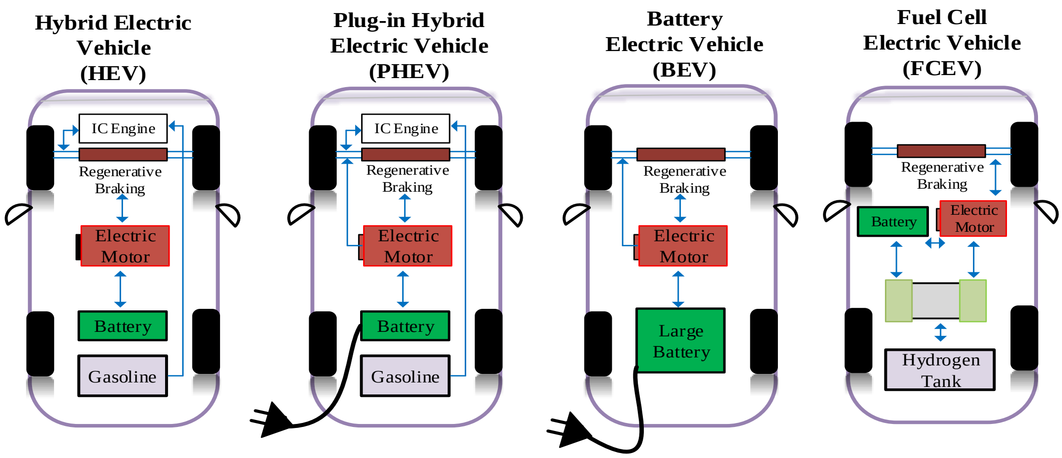

Figure 5. Four types of electric vehicles [37, 38]

Fuel cell EVs split electrons from hydrogen molecules to produce electricity to run the motor. The additional energy source battery connected to the fuel cell has zero emission [36]. In [37, 38], Hybrid Electric Vehicle (HEV) are powered by an internal combustion engine and a one or more electric motor, which uses energy stored in batteries. A hybrid EVs battery cannot be charged by plugging in operation. Instead, the battery is charged by the internal combustion engine and regenerative braking.

Article [39] consider that regenerative braking refers to the operation of an electric motor in reverse, which applies a braking force from electromagnetism. By charging the battery, the kinetic energy is recaptured in all four EVs as shown in Fig.5. The specific driving modes with variable levels of regenerative braking are available on EV types. The four types of EVs and their electric drive component, the automotive industry used in the market, set of problems and features of each type are listed in Table II.

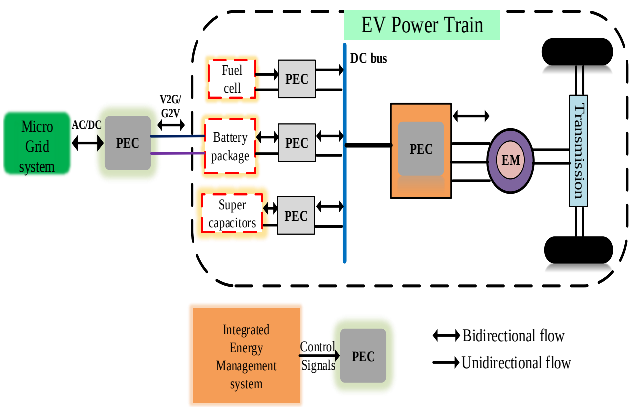

Figure 6. New energy storage sources [40]

In [40] mentioned EVs powertrain's main components are electrical machines (EM) propulsion, power electronic converters (PEC) and new input energy storage sources such as fuel cells, batteries, and supercapacitors. The technology development in a battery storage system using both unidirectional and bidirectional energy flow from microgrid system to PEC was also addressed. Authors in [41] showcased the integrated energy management system which can supply from oil, biomass, coal natural gas, nuclear, and zero emission energies hydroelectric, wind and solar. The connection between EM to PEC, the bidirectional power flow from EM acceleration and deacceleration mode for regenerative braking capability for EVs to increase the battery energy are as shown in Fig. 6.

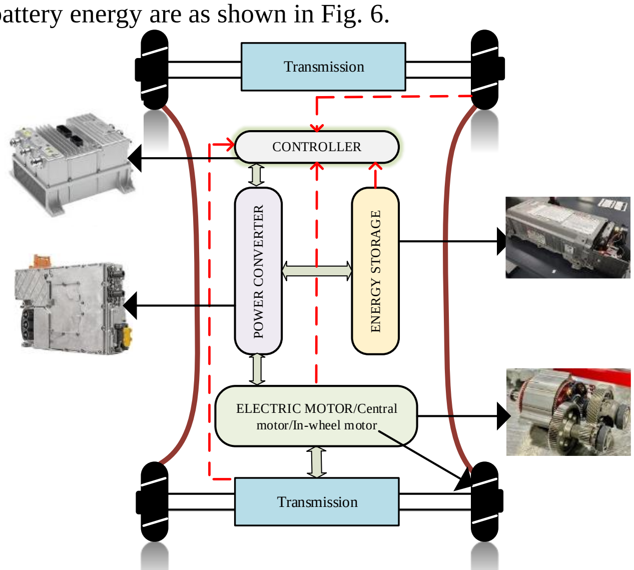

Figure 7. Background of electric powertrain [41]

EVs structure has internally connected four important parts electric motor, power converter, controller, and energy storage (battery) as shown in Fig.7 [41, 42]. EVs were driven by electrical machines during the last five decades using motors with low cogging torque BLDC, low-cost material interior PMSM, increased efficiency IM, and torque ripple less SRM. In [64] Power electronic converters were used to convert the input source based on the energy storage supply system converter which chooses chopper, inverter, and resonant converters. The different types of powertrain configuration and electric motors (e-motors) were discussed in the next section.

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TABLE II **Electric vehicle sources and features [37, 38]**

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

III. Electric motors used in EVs

A. Types of motor configuration in EVs

The electric motors are available in different drive train options. The placement of the electric motors (e-motors) plays a very important role in the power delivery and purpose of the vehicle. EVs can come in different configurations such as single motors, dual motors, triple motors and four motors in each wheel. Some EVs like Tesla using single and dual motors set-up, the wheels are directly connected to the motor by eliminating transmission. Model S plaid and Tesla roadster are triple motors set up, two individual motors drive each of the rear wheels and common motor drive in the front wheel. Rvian-R1T and Rivian-R1S (uses four motors) as several motors in each wheel. However, two in the rear and front wheel as called hub motors. This setup increases the eligibility and handling of the vehicle which are listed in Table. III.

B. Types of e-motors in EVs

They are different types of e-motors used in the automobile industry. When coming to EVs, there are seven types of motors with each having its own strength and weakness [43, 44]. Motors are brushed DC motor, Brushless DC motor, Permanent magnet synchronous motor, Induction motor, switched reluctance motor, synchronous reluctance motor and Axial flux ironless permanent magnet motor.

The brushed DC motor, the motor controller is not used to vary the speed in EVs. It provides maximum torque at low speed, the main drawback is bulky structure, low efficiency, heat generated by brushes. It was used in Fiat panda Elettra after major issues concerning this motor, it's not being used in EVs. The BLDC are most preferable for EVs application due to traction characteristics. The advanced technology includes BLDC motor distributed windings and has a trapezoidal current wave shape with no requirement of brush and commutator. In [45] arrangement of the magnet, motor classifies interior rotor and in-wheel rotor. Based on the flux flow path, it can be classified as radial and axial flux. However, electronic commutation produces high torque ripple and noise. The main drawback is the short constant power range and decreases the torque increase in speed used for small cars maximum of 60kW power. In [45,46] PMSM, based on the rotor place, it can be classified into surface mounted rotor SPM for low power EV and interior mounted rotor IPM for high power which is suitably well designed by high power factor, high efficiency, high reluctance torque, low heat, and simple in a package used in HEVs. It can be operated in different speed ranges without using a gear system, high torque at low speed. However, the cost of material is too high; the overall cost of EV becomes high, huge iron loss using in-wheel drive.

In [45,46] squirrel cage ACIM laminated low-cost silicon steel stator inserted three-phase stack and rotor slot both ends with rings. IMs are characterized as simple structure, low cost, high reliability, less torque ripple, and noise. However, less efficiency, low power density, inverter and control circuits are complex issues in EVs. In [47] SRM is a variable reluctance motor adopted for double salient with low-cost silicon steels. In [48] SRM has simply concentrated windings installed in the stator, simple structure, high power density, robust, high speed, least fault-tolerant and most suitable for high-speed applications. However, complexity in control, increase in switching circuits, torque fluctuation, and noise are serious issues in EV.

In [27] SynRM torque is created by the direct and quadrature axis of the magnetic circuit with no field windings or permanent magnet. It has an easy and strong construction, non-existence of rotor cageless and high permanent torque. However, low power factor, power density and complexity in control. The most advanced motors in EVs, axial flux ironless permanent magnet motor using an external rotor, avoiding iron in the slot, and stator core also absent are main advantages. It reduces the weight of the machine, airgap radial field type, and high efficiency and reduces copper loss. The main drawback is control complexity and less efficiency. Based on the comprehensive literature survey and recent research in the automotive industry selectively uses EV characteristics most suitable motors are as shown in Fig. 9.

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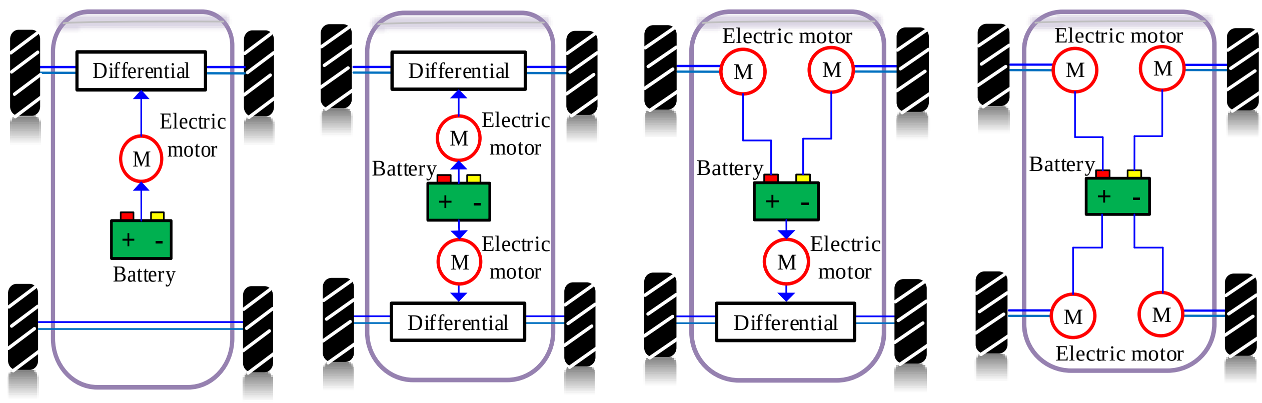
TABLE III Types of motor configuration in EVs



Centralized single motor driven powertrain	Distributed multi motor driven powertrain		
Single motor	**Dual motors**	**Triple motors**	**Four motors**
• Compact unit, High efficiency. • Fewer components needed, cheaper to build. • Tesla polestar 2, electric range 425km, top speed 160kmph.	• More HP, high acceleration, efficiency and speed. • The additional degree of the freedom in vehicle for enhancing traction and stability control. • The increased ability of the overall traction system. • Tesla model 3, electric range 575km, 260kmph.	• More HP, high acceleration, efficiency and speed. • Torque coupled and controlled in moving drive efficiently. • All wheel drive handling stability group. • Audi-etron-S, Tesla model S, and Tesla model X.	• More HP, high acceleration, efficiency and speed. • All wheel drive handling stability group. • Four small motors in wheel called in-wheel or hub motor. • Positive and negative torque individually controlled in each motor.
• Not efficient than other motors. • Not suitable for high power.	• More expensive. • Lack of standard transmission. • Control more complex.	• More expensive. • Lack of standard transmission. • Control more complex.	• Torque vectoring control in each In-wheel motor are more complex.

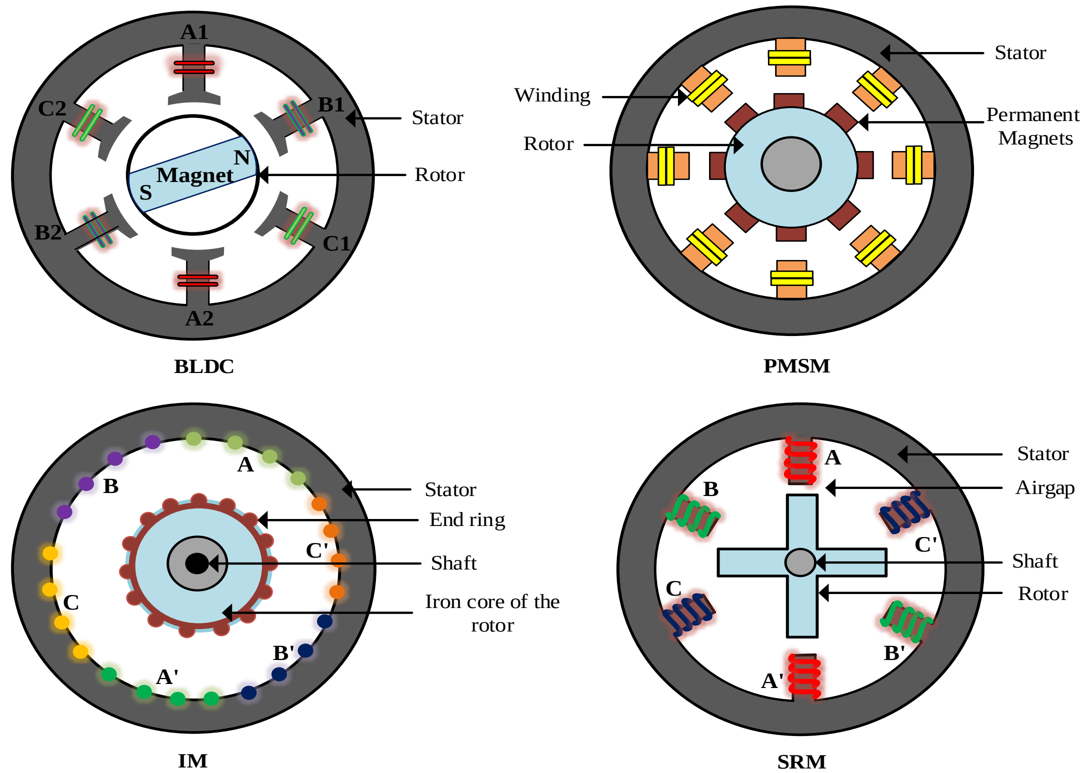


Figure 8. Types of e-motors in EVs [45-48]

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	BLDC	IPMSM	ACIM	SRM
EV Motors				
EV Company	Toyota Prius Ather Energy Scooters Yamaha EC-03 Upcoming TVS	Soul EV Nissan Leaf Toyota Prius	GM EV1 Toyota RAV4 Tesla Model X Tesla Model S	Chloride Lucas Land Rover
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.	High power density. Simple and robust. Fault tolerant. Construction cost less. High speed. Robust and efficient.
Disadvantages	PM rare earth material cost is high. Constant power range less. High Cogging and reluctancet 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.	High noisy. High torque ripple. Low torque density. Large vibration.

Figure 9. EVs motor features [45-48]

IV. BRUSHLESS DC MOTOR (BLDC)

A. Main limitations of BLDC motors

The main limitations of BLDC are high-cost Permanent Magnet (PM) material, speed range, low Efficiency, torque ripple, acoustic noise, fault-tolerant and electromagnetic interference. In [13] manufacturing a motor using PM material can be categorized based on four different earth materials which include high-temperature capability Alnico, low-cost ferrite, high corrective force, remanence NdFeB and maximum density SmCo. At the present state, [13,49] authors discussed the high energy density, high remanence, high demagnetization, and corrective force PM material are primarily combined with different materials such as neodymium magnet alloys and samarium alloys. In [50] PM materials such as Alnico and ferrite affect the demagnetization ability and torque density, because of less coercivity, low remanence, high-temperature effect, and low energy products in their magnetic properties. However, in [50] authors discussed the minimum coercivity ferrite (Fe) gives the best field weakening capacity and rotates at maximum speed. Magnets alloy with iron oxide are common to earth free low-cost material for inner and hub BLDC drives. The magnet placed in the motor classifies inner and in-wheel rotors that are suitable for EVs. The inner rotor magnet is classified surface mounted, inserted, and buried.

The most suitable low power EVs are: In-wheel rotor type motors. In [51] proposed selecting a better EV motor, first analyzes the drive parameters and physical properties of the materials. The main challenge in this motor is high torque ripple, acoustic noise, fault-tolerant, and EMI. These factors can be mitigated using motor design and controller aspects. In [52] state that output design is based on careful consideration of geometric parameters in EVs. BLDC is mainly used in small cars less than 30 kW because of the speed-torque characteristics performance in EVs.

1. BLDC In-wheel motors

In [52,53] considered BLDC hub motor permanent magnets are fixed to a ring on the exterior to stator coils called the rotor and the ring is kept in motion whereas the rotor is kept stationary as shown in Fig. 10. The hub motors are preferred for lightweight electric vehicles. Since it is easy to fix a wheel over the hub motor is preferred for electric vehicles. BLDC hub motors are driven using both sensor and sensorless motor controllers. The main disadvantage of using hub motors is (i) Using hub motors increases the weight at the power-driven side which decreases the vehicle stability, (ii) Delivering uniform torque is too difficult and (iii) Mechanical stress experienced by hub motors are more, compared to normal BLDC. The exterior rotor connection produces less torque ripple, compared to the interior PM rotor.

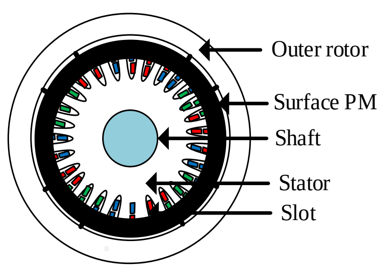

Figure 10. BLDC Hub motor

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2. BLDC Inner rotor

In [54] proposed PM are fixed to a ring on the interior to stator coils and the ring is kept in motion whereas the stator is kept stationary called inner rotor as shown in Fig.11. In an EV power train, the torque ripple is produced based on the structure of the motor, the nature of the motor operation, and motor control. These can be mitigated by changing the motor structure by reducing airgap between magnet and slot conductor, during commutation process controlling the converter switch on and off at proper interval.

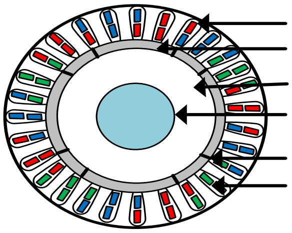

Figure 11. BLDC Inner rotor

In [55] considered BLDC using concentrated windings in stator side waveform is trapezoidal back EMF, there are no windings in rotor side it reduces the copper loss and increases efficiency. BLDC drive has an electronic commutator voltage source inverter and sensor. It produces maximum torque per ampere at a constant power region. In [16, 29, 55] author discussed motor speed can be controlled by vector control, direct and indirect torque control for above the base speed. In EV drive BLDC, mainly uses minimum power rating: In BLDC outer rotor type produce less torque ripples compare to inner rotor type. The main source of torque ripples for BLDC are the nature of motor, motor structure, and motor control. In [56] nature of BLDC can generate different torque ripples is shown in Fig.12 The main challenge for BLDC is to improve the efficiency and reduce the torque ripple are discussed in the following section.

In [57] considered BLDC producing less efficiency, connecting additional field winding also gives the enhanced speed range in addition to increasing the overall efficiency of the motor are listed in Table IV. The PM and field winding combined hybrid motor arrangement structures are too restrained with complexity and cannot attain the speed range of EV vehicle requirements. In [58,59] proposed BLDC power converter conduction angle can improve the efficiency in EV drive and speed range increase more than four times then base speed and after a certain range of speed, the efficiency starts decreasing due to demagnetization.

BLDC buried PM mounted in the rotor can provide more air gap flux density, surface mounted rotor requires less amount of PM material. These both types can improve the efficiency compare to inner motor.

C. Torque ripple control techniques

In [60, 61] stated that BLDC air gap is present between slot magnetic field and flux linkage, the back EMF distributed non-sinusoidal waveform generates torque ripples. The vibration and noises are developed in EV for both inner and outer rotors. This effect causes low power in the motor which creates an overloading capacity effect by rotor magnet to investigate different control methods to mitigate torque ripples.

In [62] author discussed BLDC has commutation angles for every 60 degrees and circulates unevenly helices every 60 degrees in the air gap magnetic field, resulting in minimum torque ripple. Pulse Width Modulation (PWM) control algorithm were used to eliminate torque ripple, induced by the stator magnetic field. In [63] proposed sensorless controller, the effects of PWM mode the commutation switching angle torque ripples were mitigated. The PWM control method produces current by BEMF during the turn-off process to reduce the torque ripple. The PWM chopping method for low power rating motors to reduce the torque ripples. In [63] proposed torque ripple reduction using two switching methods are PWM chopping strategy and overlapping method, the output torque is high and torque ripples are very less compared to overlapping method. The other techniques, when varying the input voltage, the torque ripple is minimized. In [63] proposed method has input voltage which reduces current ripples in the conduction field and causes torque ripples. The other control techniques, cascade Buck converters are used to remove conduction torque ripple in BLDC.

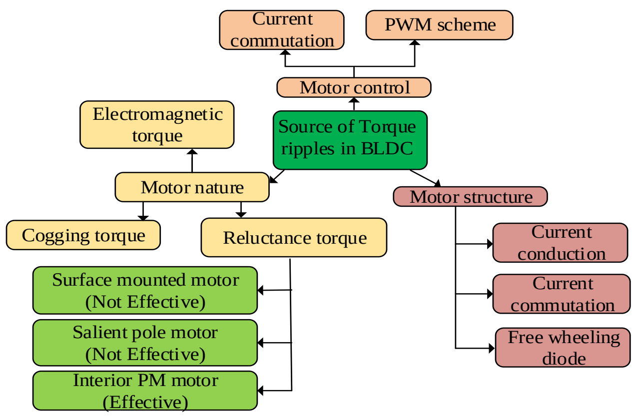

Figure 12. Source of torque ripples in BLDC [56]

TABLE IV Design techniques to improve the efficiency

Method	Adopted technique	Advantage	Disadvantage	Ref
stator slot opening and wedges	• Air gap windings Skewing. • Short pitch winding. • Fractional slot winding.	• Simple to implement improve the efficiency.	• Vibration. • Audible noise.	[57]
Rotor Magnet pole arc	• Rotor magnetic pole arc width positions.	• Improved efficiency. • Improved torque.	• Increasing noise.	[58,59]

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TABLE V **Control techniques to mitigate torque ripples**

Method	Adapted techniques	Advantages	Disadvantages	Ref
Modified PWM control	• PWM chopping method. • Low-cost digital control technique.	• Higher output torque lower ripples. • Minimum cost. • Motor control hardware is complex.	• Eliminating only torque ripple caused by stator magnetic field.	[62]
DC bus voltage control	• Cascade buck converter	• Reduce torque ripples. • Harmonics using analytical computation.	• Eliminate only the commutation torque ripple.	[56,64]
Current control-based technique	• Repetitive current control. • Predict current commutation. • Eliminate negative DC.	• Low-cost drive strategy. • Smooth commutation.	• Commutation torque ripples. • Minimized torque ripple during low speed.	[65,66]
Phase conduction method	• Current overlapping method.	• Miniature motors used sensor less control for BLDC motors.	• Reducing the torque ripple components.	[63]
Model predictive control	• Estimation function using virtual vector delay time MPC-FCS.	• Good dynamic performance and robustness	• Number of subsystem parts increases.	[78]
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.	[67,68,79]
FOC control	• Flux and current in the steady-state.	• An efficient control flux and torque.	• SVPWM complex to reduce the torque ripple.	[76]
Model Adaptive control	• Fuzzy-logic controller for speed control. • Reduction of torque ripples.	• The gain of the filter is adapted to reduce torque ripple.	• High sampling rate. • Maximum precision requires high computing power. • Increasing the cost of digital controllers.	[73,74]
Soft computing technique	• Neuro-fuzzy observer. • Artificial neural network (ANN)	• Minimize the torque ripples using soft computing techniques.	• Complex computational algorithm. • Real-time difficult.	[75,77]

In [64] proposed BLDC with minimum inductance requires a more than two-level or multilevel inverter. In this multilevel DC connection inverter will significantly reduce current ripples. In [65] proposed two switching current estimation, DC sensing-based commutation and exclusion of negative DC voltage are reducing the torque ripple. In [69] the multi-objective optimization technique in which proper duty ratio control will equalize the curve of the current slope of incoming and outgoing phases during the interval of commutation. During the commutation interval, the system suppresses the spikes and dips superimposed on the torque and current responses. In [73] proposed adjustment the advance step angle control system is the foundation of the proposed method to reduce torque ripple. The rectangular shape current phase waveform from the speed and torque response characteristics method to minimize the torque ripple.

In [67] stated that DTC flux linkages between stator and rotor angles determine the electromagnetic torque in a BLDCM. As a result, DTC can provide a high dynamic response. DTC has many advantages in terms of structure simplicity, particularly not requiring any coordinate transformations or PWM generation. In [68, 79] DTC technique is mainly used for EV drives for commutation torque ripple minimization. The technique works by reducing the difference between the projected torques and the reference command. The DTC phase current waveform adjustment in steady-state electromagnetic torque, effectively removing commutation torque ripples, particularly at high-speed rotation. In [72] author discussed the applied to electric vehicles, the concept is aimed to achieve continuously variable transmissions. To achieve torque control, the control scheme uses only one current sensor to calculate the DC bus current, rather than using two or three current sensors. Constant power and torque for mechanical variable transmissions, it can be achieved by selecting field weakening and closed-loop torque control with phase advance angle. In [71] proposed reluctance torque ripples were measured using a ripple index, and the calculation work was done using FEA simulation technique. In [73, 74] author discussed the torque ripple is reduced using a wide-angle wave control system. The proposed sensor less control strategy, reduces torque ripple while increasing torque.

In [75] proposed an intelligent controller has two fuzzy controllers combined to make complex in, the initial controller is intended based on the torque error to select the proper voltage vector control, and second one stator flux linkage angle, and stator flux linkage electric error to minimize the torque error. The fuzzy controller with variable factor is used to control the voltage vector action time based on the torque error difference and torque error. In [77] considered fuzzy modulation, the total torque ripple is reduced in a BLDC caused by phase commutation. The fuzzy logic using closed loop speed and current controller with hysteresis are used in the proposed to minimize the

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torque ripples. To improve the performance characteristics of EV drive powertrain system, the fuzzy includes PI controller instead of traditional speed PID controller to reducing the torque ripple. The torque ripples are integer multiples of both stator and rotor pole numbers least common multiple (LCM) proposed to reduce the torque ripples. The injected harmonic current to minimize torque ripple in the interior BLDC has been suggested by the researchers.

In [76] stated that PWM can be implemented in FOC using a variety of strategies such as IFOC, the most prominent of which being space vector PWM, sinusoidal PWM, and third harmonic injection PWM to minimize the torque ripple compare to DTC. The neural networks, fuzzy logic, and genetic algorithms are examples of soft computing techniques that can be utilized in situations that need extreme precision and control techniques for EV drive to reduce the torque ripple.

The most common problem in BLDC for EVs are torque ripple, fault tolerance, and electromagnetic interference. The torque ripple is most needed to control, this problem can be mitigated using advanced control techniques such as FOC, DTC, intelligent control and their features are listed in Table V. These techniques are a good steady-state and dynamic performance to minimize the torque ripple as shown in Fig. 13. Based on the survey in-wheel BLDC motor are suitable for low power EV, generates less torque ripple.

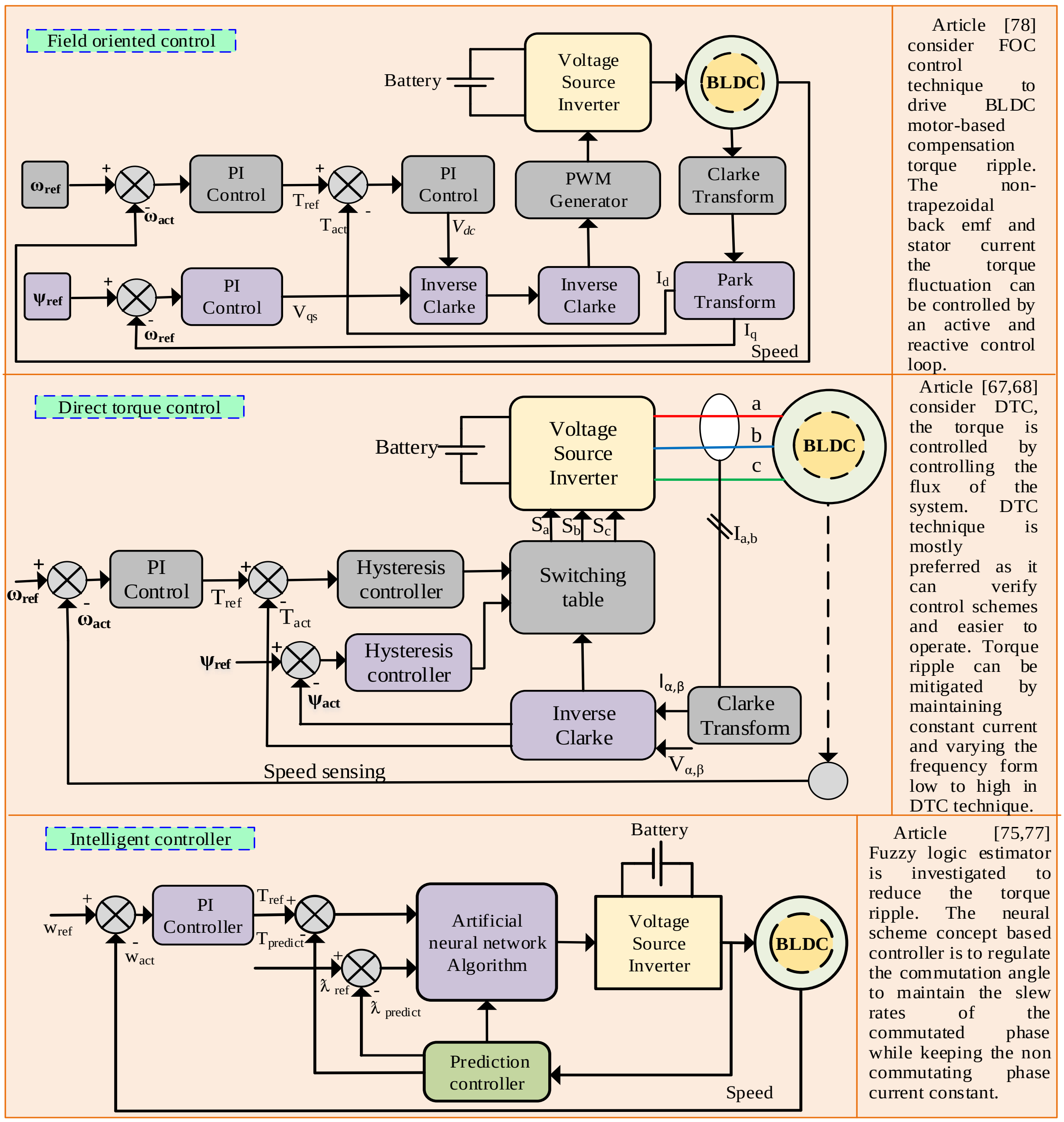

Figure 13. **Control techniques FOC, DTC and IC for BLDC.**

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V. PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)

A. Types of motor topology

PMSM is similar to BLDC construction, materials, inner and in-wheel rotor structure. The main drawback using high-cost magnet material, torque ripple, fault-tolerant as shown in Fig. 14. In [80] proposed low-cost and maximum temperature ferrite-based PMSM is a viable option for EV drive trains due to its extremely high available earth material, but the main drawbacks are low coercivity force and low energy density. In [81-83] considered the new motor topology techniques have been suggested, PM assisted synchronous reluctance motors, spoke type PM motors, axial flux PM motors. In [84] considered high grade and low-cost PMs are required in auto industry.

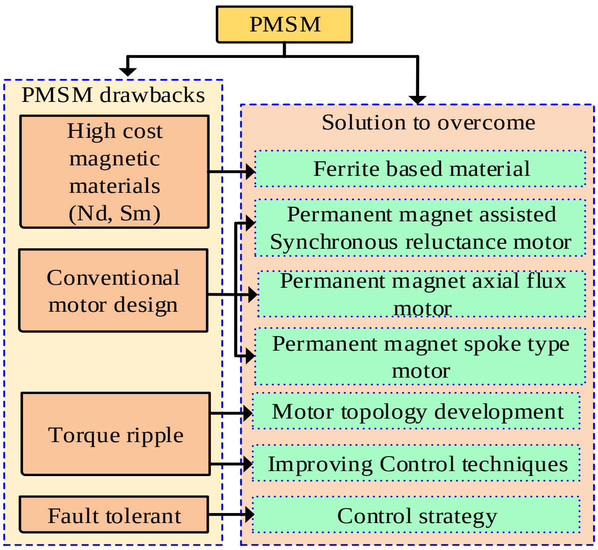

Figure 14. PMSM limitation in EVs

1. Permanent magnet assisted synchronous reluctance motor (PMAsynRM)

In [85] considered the difference between IPSM and PMASynRM is the ratio of interior rotor permanent magnet torque and minimum reluctance torque to total torque. Optimizing the configuration of rotor segments, rotor barriers, and rotor ribs the PMASynRM is not fully compensated for reducing the output torque as shown in Fig.15 (a). As a result,[86] this new topology can be used in combination with low ferrite PM to provide a less torque solution and minimum cost FEA analysis. In [86, 87] ferrite low coercivity magnets have space on both sides of the rotor magnetic pole as flux barriers with different combinations on line-shaped, V-shaped, U shaped to prevent the stator magnetomotive force to avoid demagnetization as shown in Fig.17 In [87] authors suggested a tapered flux barrier to solving this problem which is analyzed to disperse the flux and minimize demagnetization.

2. PM axial flux motor

In [82, 88] compared with the axial flux PMSM and radial flux PMSM, the axial PM has the advantages like compact structure, high torque density, and low-cost PM earth material. In [88] consider axial flux PM topology at low-cost ferrite for high torque density is shown in Fig.15 (b). In [89] proposed method to construct ferrite axial flux motor material with different rotor segmented modifications can be effectively used in reluctance torque for minimum magnet torque ripple. In [19,90] number of condensed windings on stator slots increases to distribute the magnetic flux and flux linkage is demagnetized quickly when using Fe material.

3. PM spoke type motor

In [19] comparison to the other PM motors, the spoke-style PM was used reluctance torque for optimizing the rotor design for maximum magnet volume and efficiency. In [91] consider the spoke-style motor can be combined with ferrite to create a low-cost, high-performance PM motor as shown in Fig. 15(c). In [92] the spoke type ferrite PM motor can currently achieve the same high torque density as the rare earth material. The rotor magnet gets more stress due to ferrite PM demagnetization. In [93] the extra space is not used fully in ferrite PM volume to increase torque density rather it is used to improve the demagnetization quality. The PM magnetic flux barrier is mounted above the airgap which makes a large volume of spoke structures.

The main drawback of PMSM for EVs are high magnet cost, torque ripple and fault-tolerant. It can be minimized by changing motor magnet topology modification and advanced control techniques are discussed in the next section. Techniques discussed for conventional and in-wheel motor PMSM.

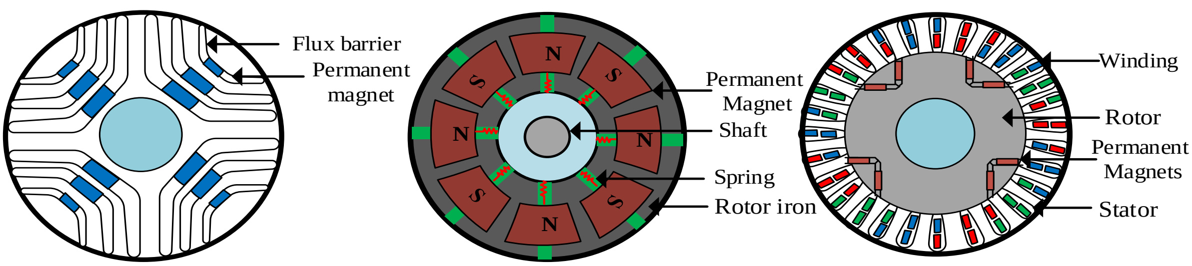

Figure 15. (a) PMASynRM (b) PM Axial Flux (c)PM Spoke Type

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B. Torque ripple reduction techniques

In PMSM the torque ripple exists between the non-sinusoidal flux density distribution around the air gap and stator slot air gap creates variable magnetic reluctance operation. A wide range of high-power applications is essential to achieve smoothness in the torque quantity. The torque ripple finite element analysis using electromagnetic design 2D and 3D for all the types of PMSM for EV application is shown in Fig.16.

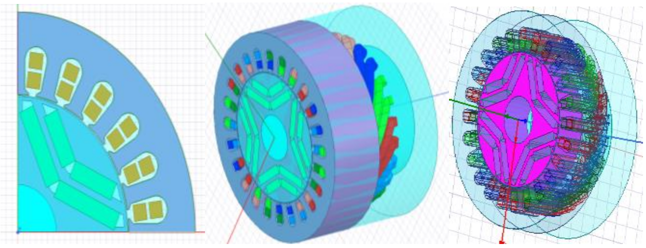

Figure 16. (a) FEA Analysis PMASynRM (a) 2D (b) 3D (c) Rotor flux density

1. Motor topology developments

In [94] considered motor design view skewing rotor magnets, stator lamination stacks, and arranging proper stator winding distribution are used to reduce the cogging torque to a certain limit that cannot be eliminated. IPM motor four generation e-motor rotor magnet structure has saturable bridges, saturated ribs, non-magnet ribs with high strength and dual space nitrogenated bridges as shown in Fig. 17. A recursive least square estimation algorithm is used to calculate the performance parameters of inductances for Interior Permanent Magnet Synchronous Motor (IPMSM). In [95] proposed slot opening width and permanent magnet width generate PM torque ripple. The minimum torque ripple tends to have one or two different permanent magnet widths depending on the number of slots per pole per phase. This method minimizes the third harmonics of air-gap flux density.

TABLE VI PMSM four generation Pirus motors generation

Key dimension	2004	2010	2016	2017
Stator (OD) mm	269.2	269.2	269.2	215.54
Rotor (OD) mm	161.80	161.80	161.80	140.5
Stack length, mm	58	50.8	50.8	61

OD-outer diameter

The IPM motor used in EVs requirements for better powertrain over the change last one decade. The four-generation e-motors changed their motor size which includes stator, rotor diameter and stack length are listed in Table VI. The IPM motor has drawbacks at high loss at high speed, high current at high speed, need position sensors, complex manufacturing, cogging torque and back EMF at no load.

2. Control Strategy Improvements

The PMSM producing high torque ripple and fault tolerant are the main problem for the EV drive train. The DTC, FOC, MPC, and other intelligent control algorithm are used in the PMSM drive train to minimize the torque ripple features are listed in Table VII. The stator flux linkage and rotor development of advanced control technique strategy, different flux, and torque control methods has been proposed to minimize the torque ripple as much as possible.

In [31] considered MPC to minimize cost function with single controlled variable, improving steady state and dynamic performance using virtual vectors for in-wheel motors to minimize the torque ripple. In [32, 96] MPCC proposed good fault tolerant capability for in-wheel motor using virtual vector compared to conventional control techniques. In [30] proposed sensor less control and-sliding mode scheme combined with duty cycle MPC for in-wheel motors which improve dynamic performance and robustness system. In [97] DTC provides a better dynamic response which is the main advantage of the DTC algorithm and it has a simple structure. PMSM-DTC scheme is improved to minimize the torque ripple by using an active null vector modulation strategy.

In [97] proposed strategy improves the performance of DTC by combining characteristics in a steady-state with faster torque dynamics with low torque ripple. By the application of the tooth shape optimization method, cogging torque can be reduced in permanent magnet motors. An optimum tooth shape has been achieved by the implemented algorithms, starting from three basic shapes. In [98] proposed method, the magnetic saturation could be effectively reduced at the rated torque and the torque ripple is reduced. This method uses an effective real-time inductance measurement method using the FOC to obtain inductance distribution in the rotor position. In [99] stated that the nonlinear analysis saturation effect was analyzed by the proposed simple active cancellation strategy to minimize the torque ripple at each electric angle. The most promising traditional control techniques such as MPC, DTC, and FOC as shown in Fig. 18 and Fig. 19. and their mathematical model analytical equations as shown in Fig. 20.

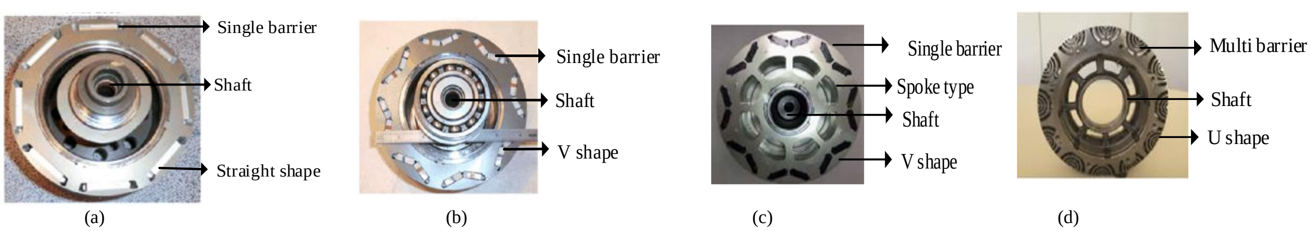

Figure 17. Four generation e-motors Pirus (a) 2004 Prius PM split, 33kW,274VDC,6krpm (b) 2004 Prius single-V, 50kW, 500VDC,6krpm (c) 2016 Chevy Volt IPM motor,60kW,650VDC,13krpm (d) 2017 Prius surface grooves53kW, 580VDC, 17krpm [99]

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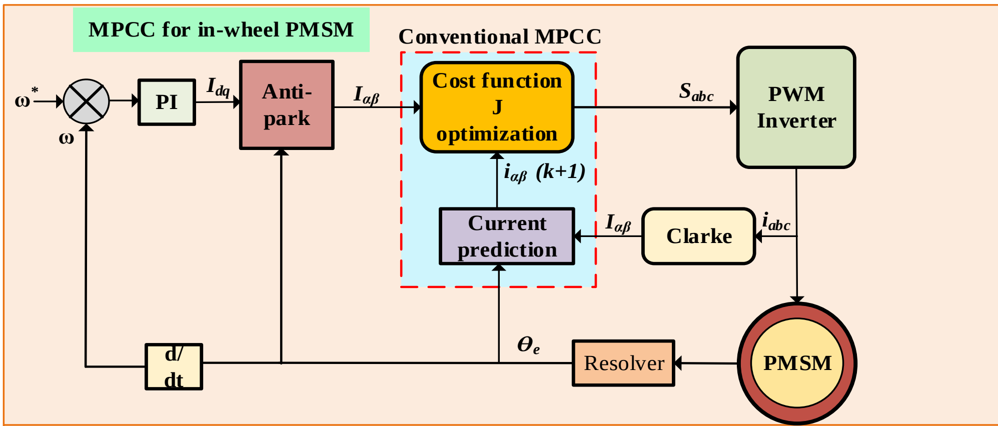
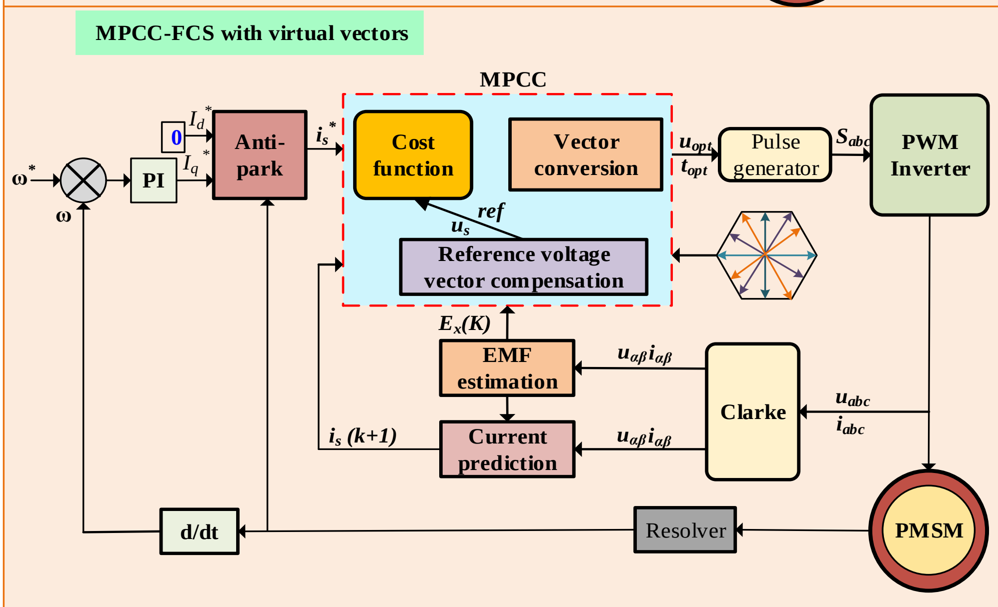
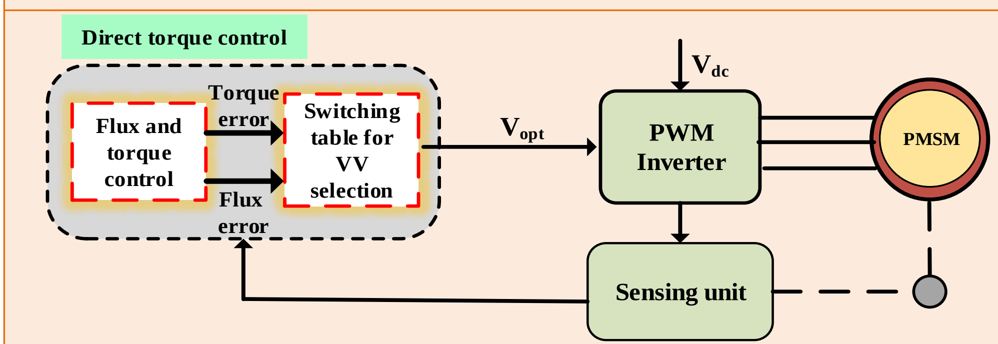
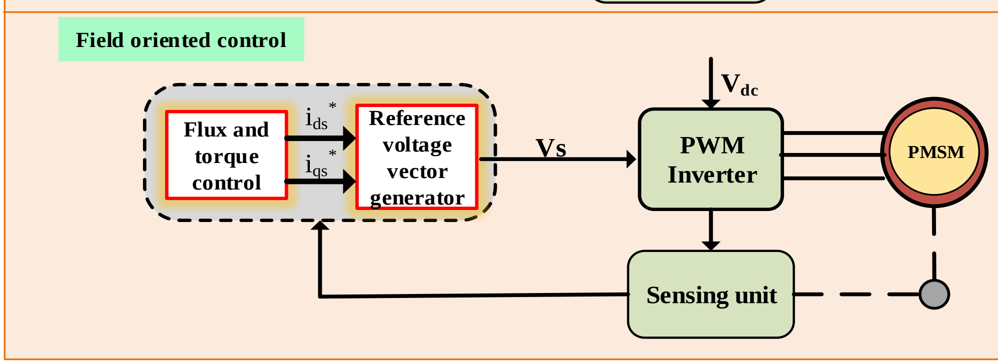
	Article [31,96] proposed a conventional MPCC minimize cost function with a single controlled variable but this fully enumerating voltage vectors causes a large computational burden and steady state performance is not accurate.
	Article [31] proposed a finite set MPC that combines virtual vector and duty cycle to improve steady-state and dynamic performance without the need for a modulator. Article [31] proposed consist of MPCC, EMF estimation, and current prediction. Further MPCC composed delay compensation, vector conversion and reference voltage vector compensation.
	Article [97,101] proposed a DTC method control the motor with utilizing torque and flux can change very fast. This provide high dynamic response, but shows high current and torque ripple.
	Article [98,100] considered a FOC method provides good steady state behavior. The torque control in low frequency and low speed, but need sense a rotor position from observer.

Figure 18. Control techniques MPCC, MPCC-FCS, DTC, and FOC for PMSM

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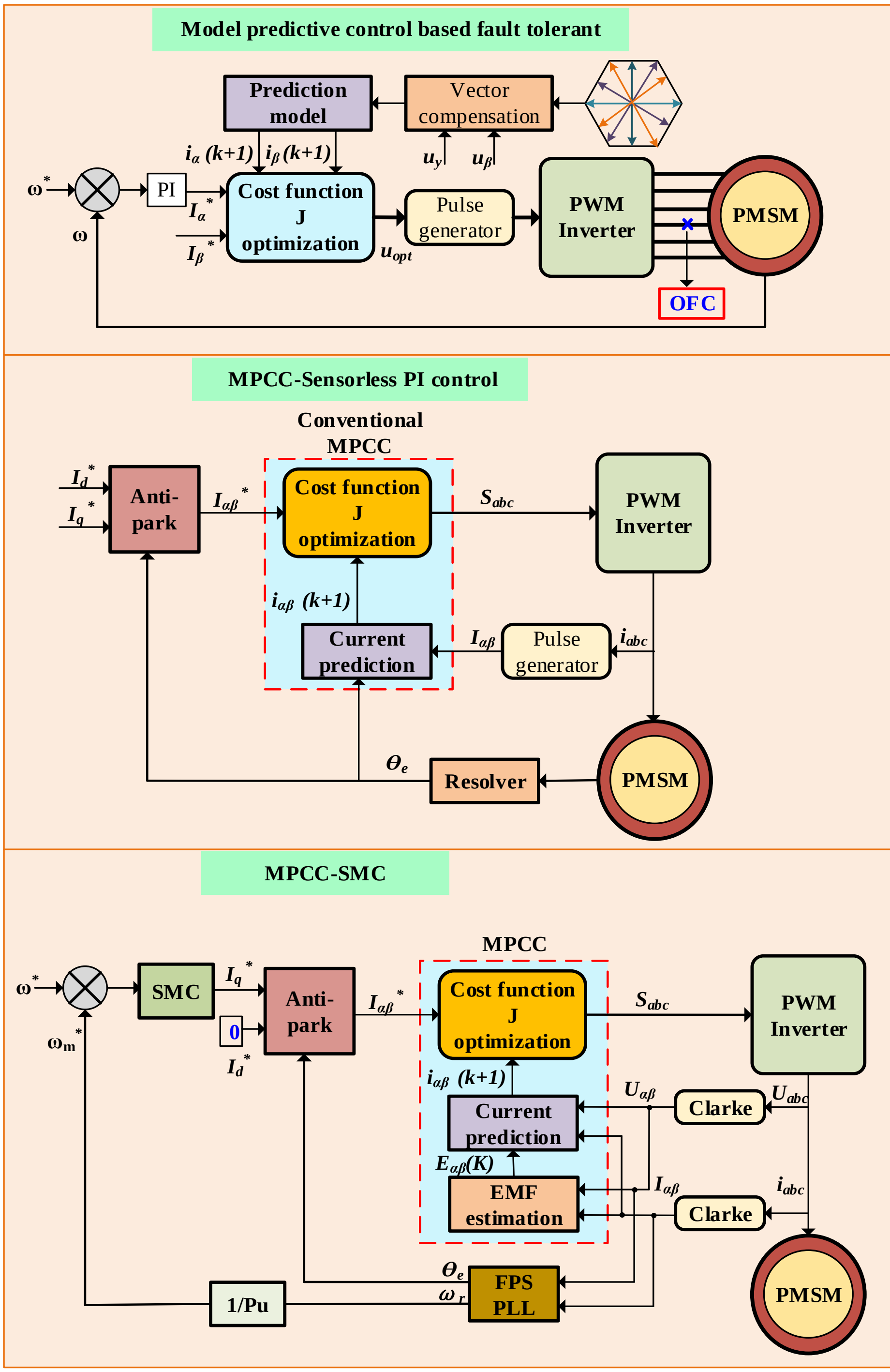

Article [32] considered the fault-tolerant scheme of the in-wheel motor after failure and proposes an MPC fault tolerant scheme based on virtual vector, which avoids the complex controller topology reset in the traditional scheme and has good fault-tolerant performance.

Article [33] proposed conventional PI sensor less control scheme MPC for in-wheel motors, which minimize the cost function and difficult to obtain satisfactory performance.

Article [33] proposed conventional PI control and MPCC, The MPCC further composed current prediction and optimization vector selection and action time. The MPCC is model based control strategy to predict future output. Speed and current controllers are combined together, including all of the state variables of the system.

Article [33] proposed a novel finite-set phase- locked loop sensor less scheme combined with duty-cycle MPC for in-wheel motors, which improves the dynamic performance and robustness of the system.

Article [33] proposed MPCC-SMC consist of sliding mode control, MPCC, and Finite position set PLL. The MPCC further composed three parts; EMF estimation, delay compensation, and optimization vector selection and action time. SMC reference current send to anti-park transformation.

Figure 19. Control techniques MPC, MPC-sensor less, and MPC-SMC for PMSM

TABLE VII Different control techniques for PMSM [13]

Method	Adopted technique	Advantage	Disadvantage	Ref
Sliding mode control	Sliding mode control theory is used to design a controller.	• Strong Anti-interference ability. • Strong Robustness. • Least affected by parameters.	• Design controller is complicated. • Existential chatting. • Computing power required is high.	[33,102]
ATC/DTC	Torque estimation with hysteresis controller regulated torque.	Torque ripple is at the desired level using direct control.	Machine parameters are derived from prior knowledge.	[97,101]
MPC-Sensor less control	Speed-adaptive pulsating high-frequency signal injection technique at low speeds.	Sensor less PMSM drives reduce torque ripple reduction.	Three additional motor parameters are needed for the compensator.	[103]

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Iterative learning technique	Periodic torque pulsations are reducing in the time domain.	Reduced the torque pulsations at maximum level.	Complex DSP-controlled PMSM drive.	[104]
Field oriented control	Flux and current in the steady-state position.	PM torque and flux control are efficient.	Complex form space vector-based PWM reduces the ripple in torque.	[98,100,105]
Model predictive control	Estimation function using virtual vector delay time MPC.	Good dynamic performance and robustness	• Number of subsystem parts increases.	[32,96]
Soft computing technique	• Neuro-fuzzy observer. • Artificial neural network.	To minimize the torque ripples, soft computing techniques are used.	• Difficult in real-time. • Complex computational algorithm.	[106,107]

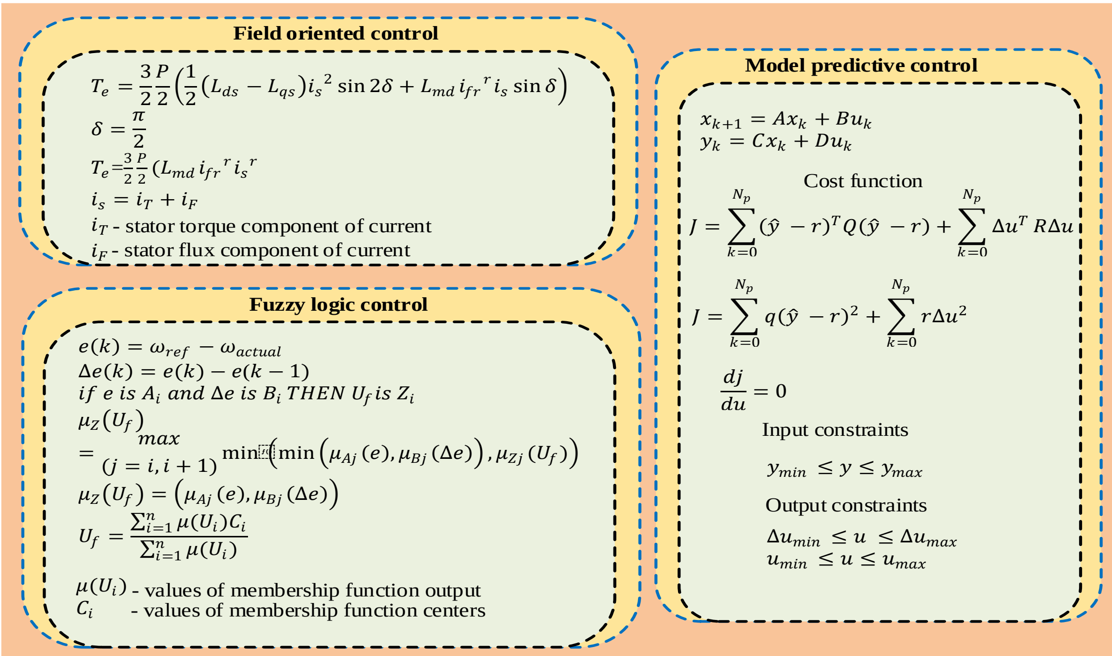

Figure 20. Control techniques model equations[96,100,101]

VI. INDUCTION MOTOR (IM)

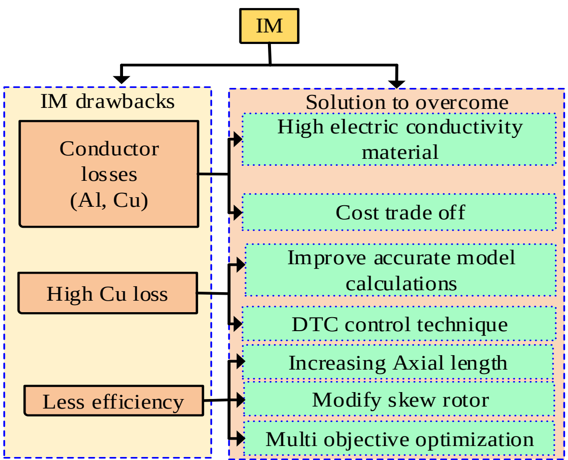

Figure 21. IM limitations in EVs

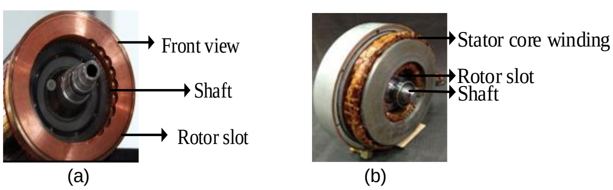

Figure 22. Tesla IM (a) Front view (b) Stator core winding

The induction motor for EVs has high loss at low speed, high current at low speed, need speed sensor, easy manufacturing, no cogging torque, high ampere-volt, Copper losses, and less efficiency. To overcome this problem using high conductivity material and control techniques as shown in Fig. 21

A. Reduce material loss

In [108] considered materials used in IM rotor conductors are classified into three categories aluminum (Al), copper (Cu), and alloy casting. Cu has an approximately 60% higher electrical conductivity than Al, making it ideal for high-efficiency EV motors. To improve the yield strength alloy is used but it does not affect electrical conductivity. Most rotors are made of aluminum because of the cost. In [109] proposed the Cu casting process has been developing for the last ten years, the fact that no robust mold could resist the maximum temperature of Cu casting resulting in high Cu rotor production costs. In [110] Cu casting technology has progressed in recent years; Cu rotors have met the cost and quality criteria for EV mass production. As a result, there is a cost trade-off between material conductivity and overall cost. The different material loss mitigation techniques are listed in Table VIII.

B. Suppressed iron loss technology

Design and control are the key directions for reducing the core loss of IMs.

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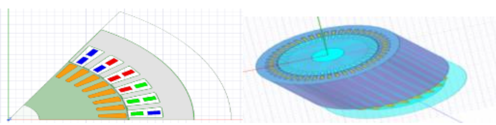
TABLE VIII **Cu loss reduction techniques for IM [13]**

IM Loss reducing methods	Technology adopted	Merits	Ref
Conductivity Increases	• Method for preventing copper loss. • Copper conductors should be used instead of aluminium conductors.	• Copper loss is reduced by Increasing conductivity.	[128,130]
Improve the precision of model calculations	• Finite element analysis in three dimensions. • Fe loss model and vector control combined.	• Increase the performance of speed and magnetic field control calculations to reduce Fe loss. • Simplified model.	[126]
Concept on Fe loss based on Control technology	• DTC combination torque constant. • Fe loss model.	• Torque response is quicker. • Fe loss is reduced. • Increase robustness.	[116, 117]
Search control method	• Minimise input power using flux iteration.	• Reduce Fe loss by being insensitive to motor parameters.	[118]
Combine search and model	• To measure the approximation value of magnetic flux distribution. • Use the Fe loss model.	• High accuracy. • Fast speed calculation. • Low Fe loss.	[127]

an accurate Fe loss measurement is needed to determine Fe loss which is minimized using a control strategy method or a design approach.

In [111] proposed for loss mitigation used simulation method is the Finite element method. It is achieved reasonably with high computation precision. 2D FEA is the most common tool for analyzing Fe loss and end shield of the motor. In [111] proposed 3D FEA has a high processing power requirement and simulation take high computational time which are considered as two drawbacks. Combining 3D and 2D FEA while calculating the losses, the end shield effects are measured by 2D and 3D FEA were complicated. Fig. 23 shows a FEA on IM drive.



(a) (b)

Figure 23. **FEA analysis (a) 2D (b) 3D**

In [112] proposed model-based controller to reduce iron loss and fast design. The Fe loss model can be divided into series and parallel models based on the form of an equivalent circuit. In [112] proposed model, the equivalent magnetizing inductance and resistors are connected in series which reduce the iron loss compare to parallel model. In [113] considered the magnetizing inductance to be frequency independent in this model, it has a simpler construction and is more practical in the series model. As the frequency varies independently, it causes a certain distortion in the magnetizing inductance. The proposed model of stator flux linkage is improved based on the stationary coordinate system and reduce the iron loss.

In [114] FOC dependent on IM parameters, the issue of drive cycle schedules, traffic states, vehicle loading and temperature. IM drives through the use of a variable flux reference selection technique, derived from the IM loss model. In [117] proposed measuring Fe loss reduction changes the flux level iteratively to maintain the input power constant. In [118] the sensorless DTC is advantages in IM-EV system. It reduces hardware complexity, minimize the size of the machine, increase reliability, and improving the efficiency. Fig. 24 show DTC based IM drive utilized flux and torque control to improve efficiency and reduce the losses.

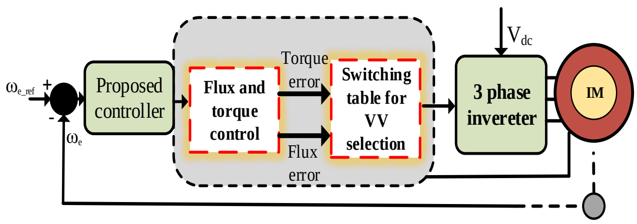


Figure 24. **DTC drive IM**

C. Improving efficiency by changing design

Article [116,119] increasing the motor shaft length is a simple method for loss suppression by structural design. This method only requires increasing the motor material to improve the efficiency; however, it may reduce the density of torque without modifying the parameter. Researchers develop [121] a skew dimension of rotor for loss suppression on torque improvement. This structure will increase the efficiency and torque, but difficult to ensure that the nature of physical tuning is efficient while minimizing the other performance sacrifices. In [120] multi-objective parameter optimization approach has been proposed to improve efficiency, which makes the motor balanced at high speed and design faster. Table IX listed techniques and features to improve IM efficiency.

TABLE IX **IM efficiency improving methods [13]**

Methods	Advantage	Efficiency, %	Density torque, Nm	Ref
Axial length increase	• Simple in implementation. • Efficiency is increasing.	88	25	[119]
Structure skew rotor, sensorless DTC	• Enhanced efficiency. • Maximum torque output.	87.3 86.4	33.17 36.17	[121,122]
Multi-objective optimization	• Number of iterations for optimization is simple to implement.	89 86.5-87.7	15.4 22.4 to 39.1	[120,123-125]

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VII. SWITCHED RELUCTANCE MOTOR (SRM)

Switched reluctance motor has an advantage compared to other electrical machines with the absence of permanent magnets or windings in the rotor. The advantage of SRM for its simple construction, robustness, fault-tolerant capability, and low-cost manufacturing. SRM flux path flow type classifies radially and axially as shown in Fig. 25. This can be further divided into a few topologies based on their pole structures. The SRM for electric vehicles is in-wheel motor and conventional motor. The main drawback of SRM for electric vehicles and hybrid electric vehicles are minimum torque density, high acoustic noise, and increased torque ripple.

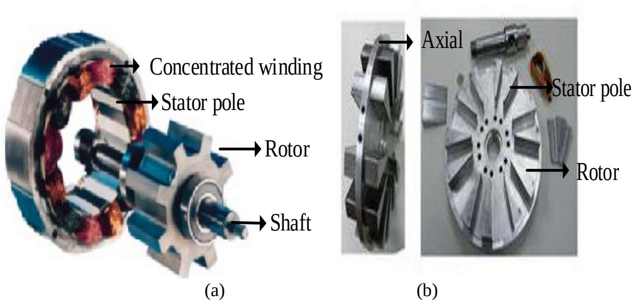

Figure 25. (a) SRM Radial flux (b) SRM Axial Sandwiched with Rotor

A. Torque Density Improvement

Double salient pole structure SRM both in-wheel and inner rotor generates average torque density. In order to improve the torque density, the changes needed in the motor design and high-density material techniques are shown in Fig. 26.

1. Flux density material high saturation

In [131] consider improving the electric loading and magnetic loading of machines cause an increase in the torque density. The machine effectively increases the magnetic loading of the material and generates high saturation flux density. Materials like Co-Fe have a flux density of high saturation to meet the condition. However, the cost is very high and it is not possible to use in the EV drive train.

2. Motor topology developments

In [132] proposed new structure of SRM was introduced to build the high torque density in the axial flux SRM, which allows the efficient use of coil end space and the inner bore. In [134] proposed the machine design specifications between axial length and torque density relationship in rotor yoke thickness, stator pole length, shaft diameter, rotor pole length, and pole arc of stator and rotor were inspected to further improve the torque density. In [135] proposed axial length parameters which are stator and rotor pole of inner and outer, rotor yoke thickness, height, and pole arc rotor were optimized separately using this relationship in design to achieve a high torque density of 42 to 50 Nm/L. It is obtained when all these parameters were changed mathematically and calculated. Improving torque density using motor topology development and high saturation flux density material technique features are listed in Table. X.

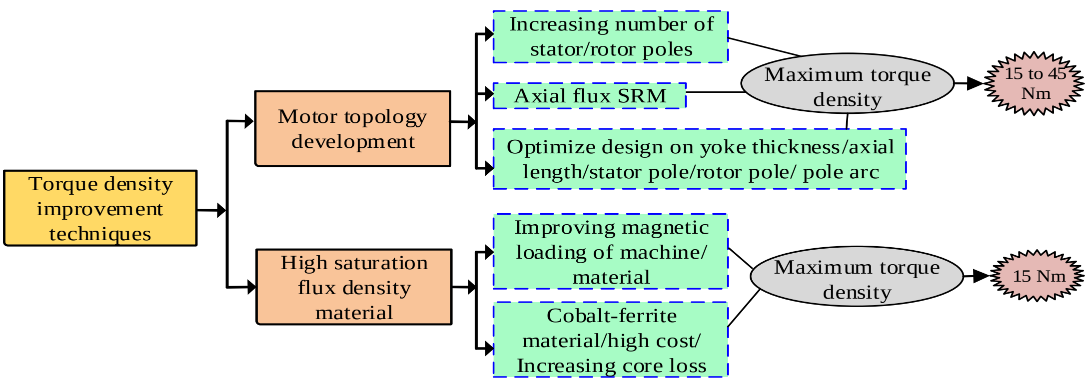

Figure 26. SRM torque density improvement techniques

TABLE X Techniques improving torque density of SRM [13]

Maximum Torque density (Nm/L)	Merits of Method	Increasing torque density techniques	Ref
15	Increased torque density.	Flux density saturation with the high material.	[131]
51	Increased the torque density.	To increase axial length winding width and change stator shape.	[132]
31	Increase torque density and reduce manufacturing costs.	Find the optimum torque density for the arc (βs, βr) of the stator/rotor poles.	[135]
45	Expand the speed spectrum of optimum output coverage by increasing torque density.	Optimize the stator/rotor shape parameters.	[133]
15 and 45	Optimized torque density torque ripple and performance	Phase excitation uses two different modes, 6 geometry parameters must be calculated to satisfy 4 terms.	[134]

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B. Reduce SRM auditory noise

Article [136] stated that most important barrier to widespread usage of the switched reluctance machine in an EV is acoustic noise. Vibration and acoustic noise are caused by the changes in the radial force of the rotor poles during converter switch on/off phase commutation. In EV, the important defect of noise reduction is from the radial force variation from the aligned to unaligned poles, which underpins the stator and rotor modification topology alternation and strategy of current control methods are shown in Fig. 28. The radial force reduction in rotor teeth alignment with different aligned flux density, magnetic flux using 2D FEA and 3D FEA is shown in Fig. 27.

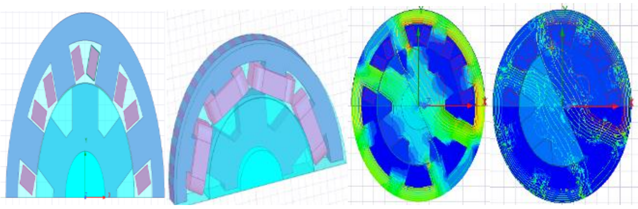

Figure 27. FEA Analysis (a) 2D (b) 3D (c) Magnetic flux (d) Flux linkage

In [137] proposed the randomizing power converter switching turns on and off-angle approach was implemented to decrease the noise produced by converter switching resonance.

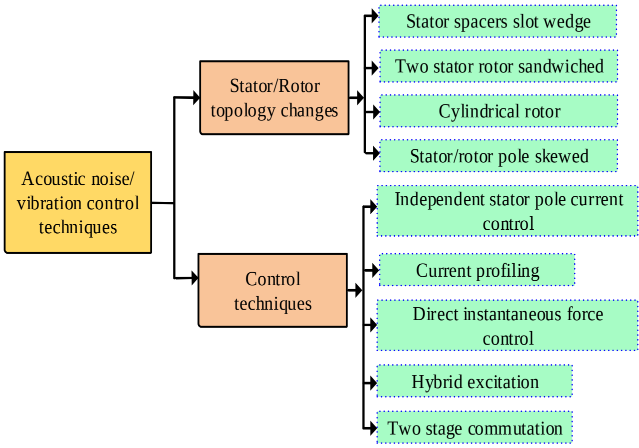

Figure 28. SRM acoustic noise reduction techniques

In [138,139] considered other topology like double stator single rotor sandwiched structure was suggested for the reduction in winding space and skewed poles. In [140] the rotor topology consisting of cylindrical configuration with thin ribs connecting the main poles was proposed causing the ability to reduce acoustic noise at a high rate. In [141] proposed noise reduction approach for resonance is the radial force harmonics reduction technique RFH. The different SRM design and control techniques features are used to mitigate the acoustic noise listed in Table XI.

TABLE XI Different techniques to reduce auditory noise [13]

Control technique	Merits	Technique Adopted	Demerits	Ref
Stator spacers inserted	• Reduced radial turbulence. • Lower windage loss. • A more durable structure.	Structural stator spacers can be used instead of slot wedges.	Fabrication is complicated, and assembly is challenging.	[142]
Two stators	• Reduced radial vibration. • Power density is high.	Connecting the inner and outer stators by rotor assemble.	Prototypes motor is expensive, and the motor structure is complicated.	[138,143]
Cylindrical rotor	• Reduced radial force and vibration. • Less windage loss.	Thin ribs connect important rotor poles.	At fast rotational speeds, a thin rib induces deformation.	[140]
Poles are skewed	• Reduced radial force and vibration. • Controlled with conventional schemes.	Stator and rotor poles are skewed at proper angles.	There are different stacks between two laminations as fabrication is complicated.	[139,144,152]
Pole currents are independent control	The optimal radial force is obtained by controlling the radial force and torque independently.	Independently connecting different pole winding and additional two poles are energized to provide the desired radial force.	Switching devices are of high cost, which generates negative torque and reduces system performance.	[145,146]
Hybrid excitation	• Hybrid excitation with its high performance. • Short tail current and ease of implementation. • Reduced noise and vibration.	Combination of one- and two-phase excitation.	Increased tail current, which makes it easier to produce negative torque and lowers torque capability.	[147]
Randomizing Turn on/turn off angle	Reducing resonance noise is simple to do.	The conduction angle should be determined at random, and the radial force range should be expanded to avoid natural frequencies.	Negative torque can be easily produced, and torque can be easily reduced.	[148,153]
Reducing radial force harmonics	Resonance noise is reducing.	To remove radial force harmonics, regulate the turn-on/off-angle.	Lower system efficiency	[149,155]
Two-stage commutation	Reduced radial vibration, easy to implement.	When the corresponding step is switched off, add a zero-voltage loop.	Produced negative torque easily with increased tail current.	[154]

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C. Torque ripple mitigation

One of the main reasons for SRM in EV power drive trains being not utilized fully is because of the high torque ripple. Much advanced torque and current control techniques, different motor design topology is proposed to minimize the torque ripple as shown in Fig. 29.

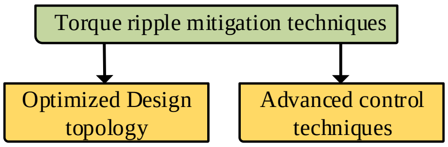

Figure 29. **SRM torque ripple mitigation techniques**

A. Optimized design topology

In [156,157] proposed new design to increase the number of interiors and exteriors in rotor and stator poles producing smooth torque, a novel SRM was built to reduce torque ripple. This design sacrifices optimum torque output. Further indexes must be included in optimization. The other parameters in the machine designing mathematical model include changing the stator and rotor pole straight and round tapered, selecting optimized stator and rotor pole arc, winding material high-density factors and electromagnetic Multiphysics performance was improved to increase the overall performance and reduce torque ripple.

In [158] considered SRM in-wheel increasing pole structure modifications in the rotor are used to reduce torque ripple as shown in Fig.30. In [159,160] proposed the slanting rotor teeth reduce torque ripple by 2%, the serrated rotor teeth structure reduces torque ripple and increases the average torque. The skewed rotors are modified to reduce torque ripple by 3% and the finned rotor teeth reduce torque ripple by 15%. The tailing pole tip and curved teeth rotor reduce torque ripple by 1.25%, the projecting notch in both stator and rotor pole reduce torque ripple by 34%, and pole arc center shift is 1.3 degree, the rotor with flux bridges reduce the torque ripple by 23%. In the two-layer SRM, one layer has high width and another layer has a small width rotor which reduces the torque ripple by 28% between two-layers shifts is 45 degrees. The asymmetric stator and rotor pole shoe reduces torque ripple by 38.8% and pole length increases 5mm. In [161] variation in stator and rotor pole arc width reduces the torque ripple and increases the average torque. As a result, the air gap between stator and rotor pole decreases and causes a reduction in torque ripple with an increase in the overall torque, the grills on the rotor teeth on each side reduce torque ripple by 2.6%.

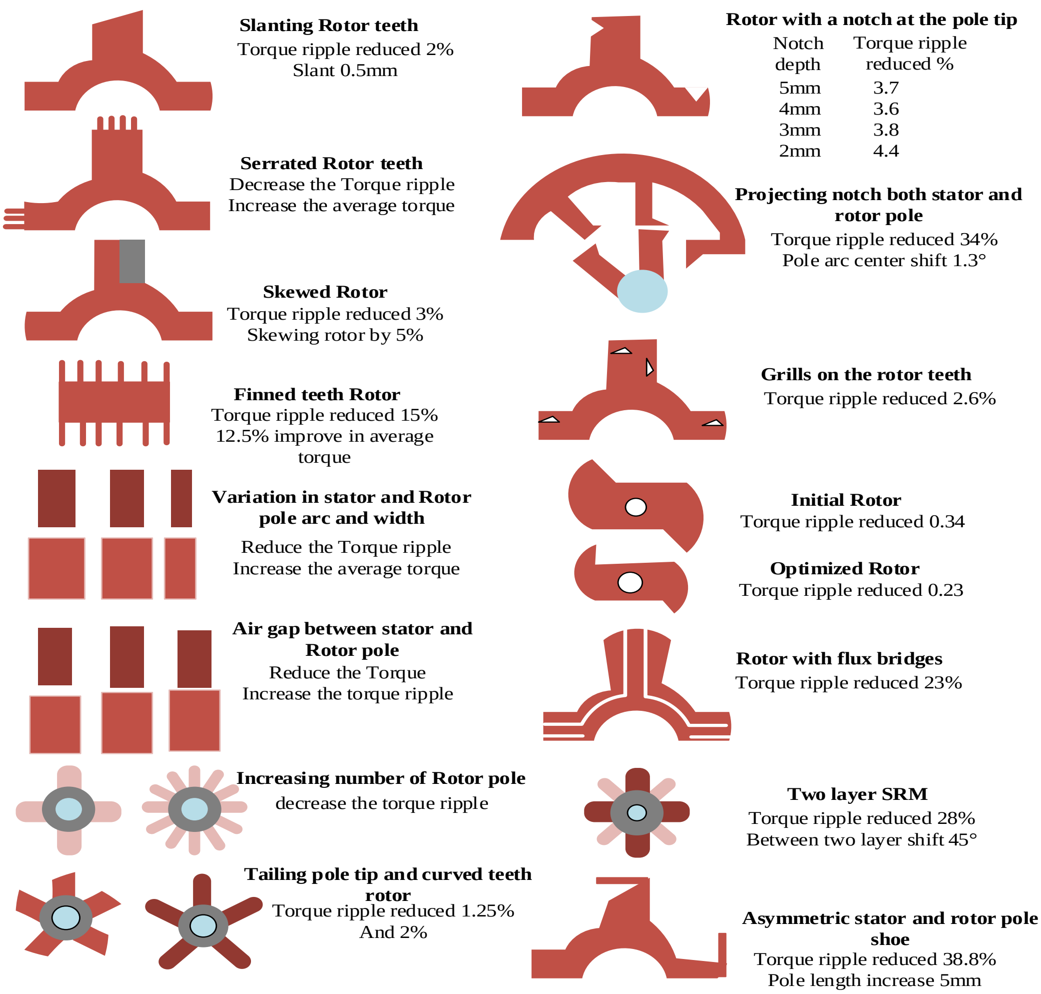

Figure 30. **Design technique to reduce noise and torque ripple[162,163]**

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B. Advanced control techniques

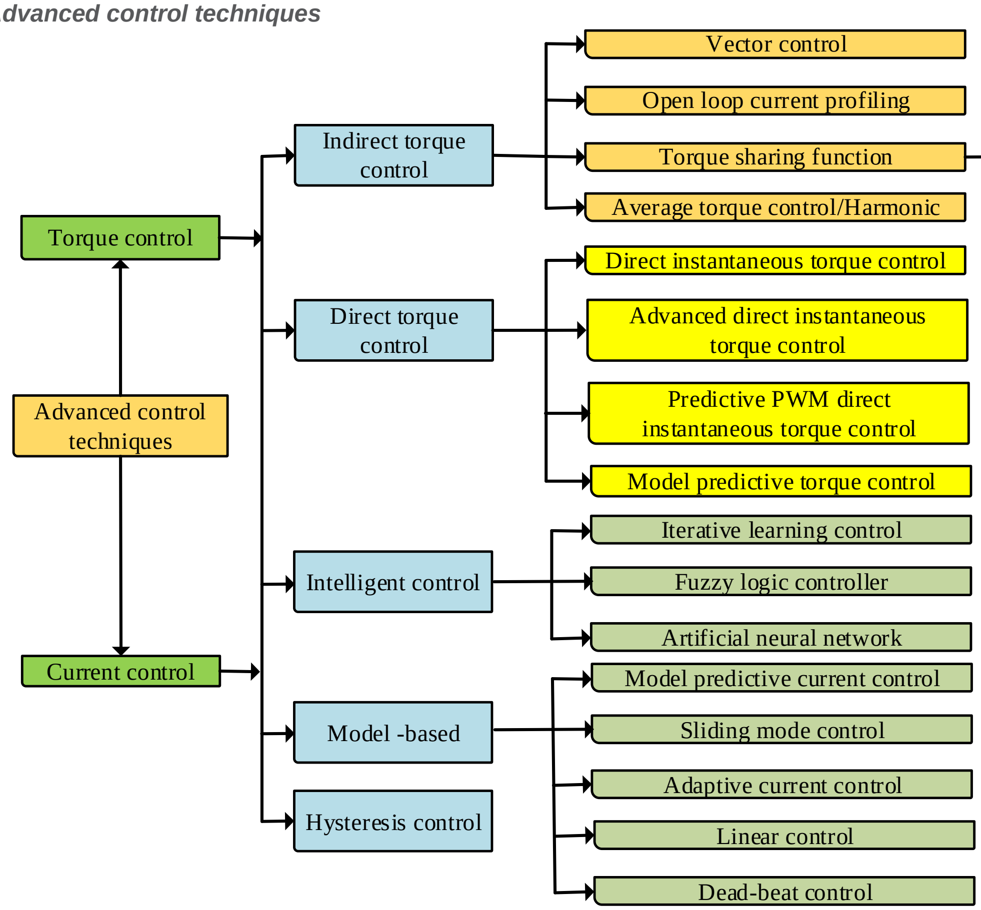

Figure 31. **Types of advanced control techniques for torque ripples [218, 219]**

The torque ripple mitigation types of advanced control techniques as shown in Fig. 31. In [164] controller is essential to remove the torque ripple during commutation. The TSF has been improved to maximum output and lower torque ripple. Linear, exponential, cubic, and sinusoidal TSFs are common. Linear, Sinusoidal and exponential TSF as shown in Fig.32.

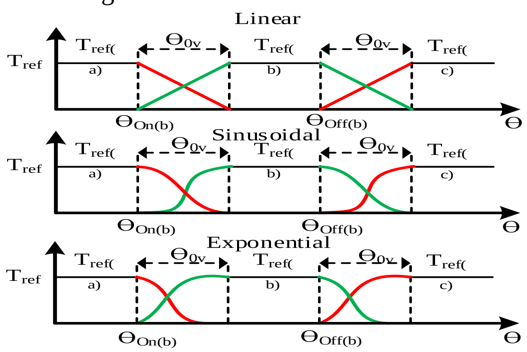

Figure 32. **Linear TSF profile, TSF Sinusoidal, and TSF Exponential**

In [165] proposed DTC controller into both the inner and exterior rotor SRM to suppress torque ripple because its vector creates the difference between real torque, flux linkage value and the reference amplitude. In [166] DITC proposed to minimize the torque ripple combination of DTC and ATC. In [167] considered MPC is characterized to forecast upcoming behavior variables of mathematical models in SRM converter switching states as shown in Fig. 33. In [249] purpose of MPC prediction is to select the proper switching on and off-state that minimizes the error between the reference value and the monitored variable as shown in Fig. 34.

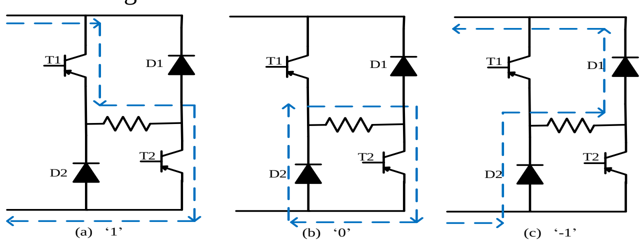

Figure 33. **(a) Magnetization (b) Free Wheeling (c) Demagnetization**

In [168] speed controller based on SMC was proposed to minimize torque ripple. The speed error was input into the SM controller and the reference current was output to power the inverter. In [169] vector control method is the most significant for AC motors. The flexible torque control method can be achieved by decoupling between torque current and excitation current method characteristics. In three types of intelligent control are iterative learning control (ILC), fuzzy logic control (FLC), and artificial neural network (ANN) techniques as shown in Fig. 35.

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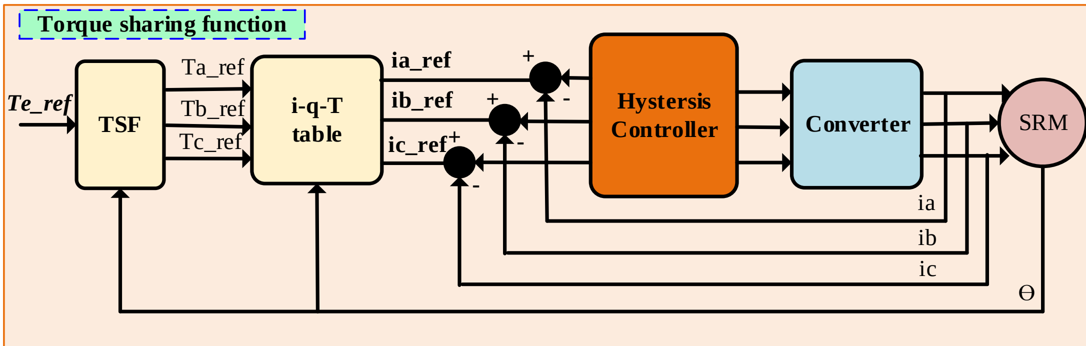
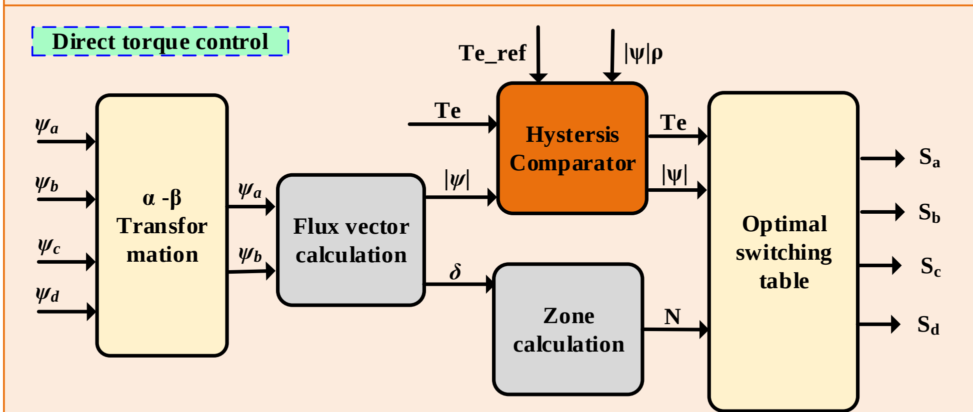
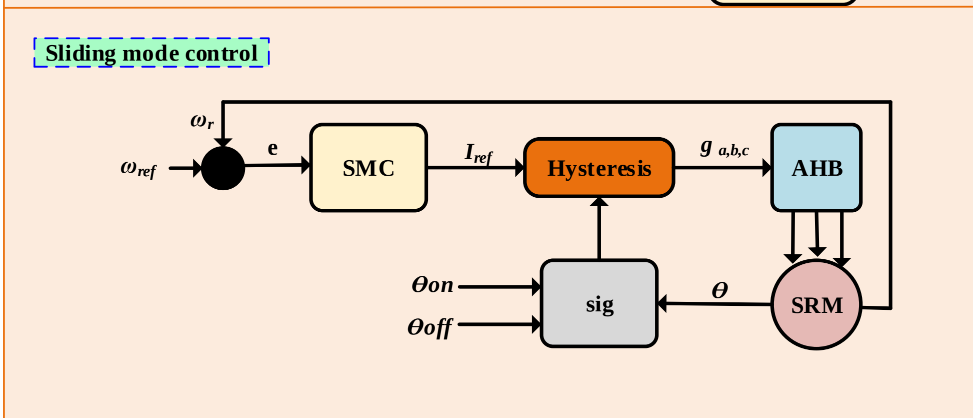


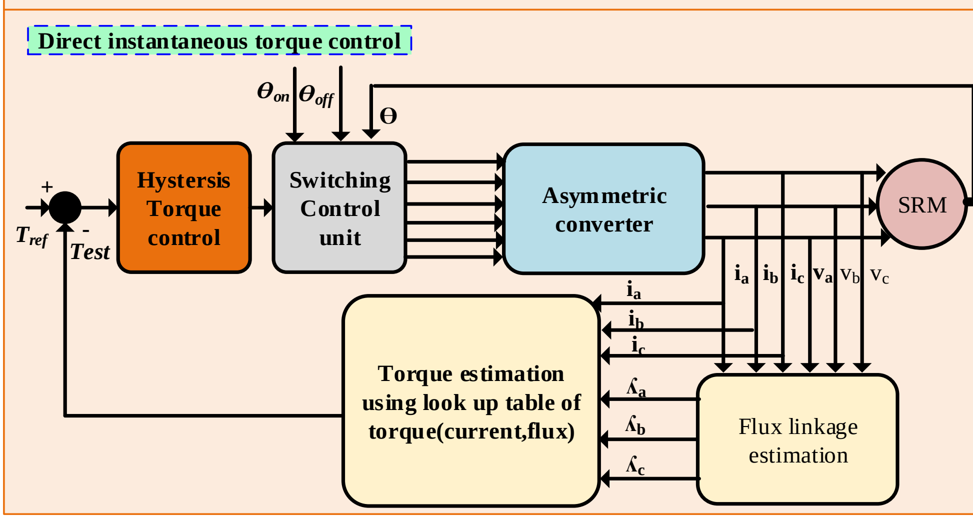
Article [172] propose a TSF function-based regulation minimizes torque ripple by optimizing the phase reference torque that the number of phase torque in the converter switch commutation region equals the average reference torque.



Article [173] proposed a DTC voltage vector selection with flux and torque using new rules to reduce the torque ripple during converter commutation which is further subdivided in vector selection rule. DTC can be improved in motors with the same pole number and estimate parameters of static characteristics are not required. The four phase transforming to two variable using park and clarke.



Article [175,176] considered a SMC high robustness which remains unaffected by parameters or interference using SMC to minimize torque ripple. The speed error was input into the SM controller and the reference current was output to power the inverter. The advantage of this method is there is no requirement for a static characteristic to switch the flux or curren.t to minimize storage space and to control the torque, the switch state is directly selected.



Article [174] stated a stator current and voltage changes using dynamic sector division rule to demagnetize minimum torque ripple and negative torque also decreases. The composed DTC and ATC. The DITC combined of torque estimation using look up table of torque (current, flux) , flux linkage estimation and hysteresis control loop. Keeping proper commutation turn on and turn off angle.

Figure 34. Block diagram of Control techniques TSF, DTC, DITC, and SMC

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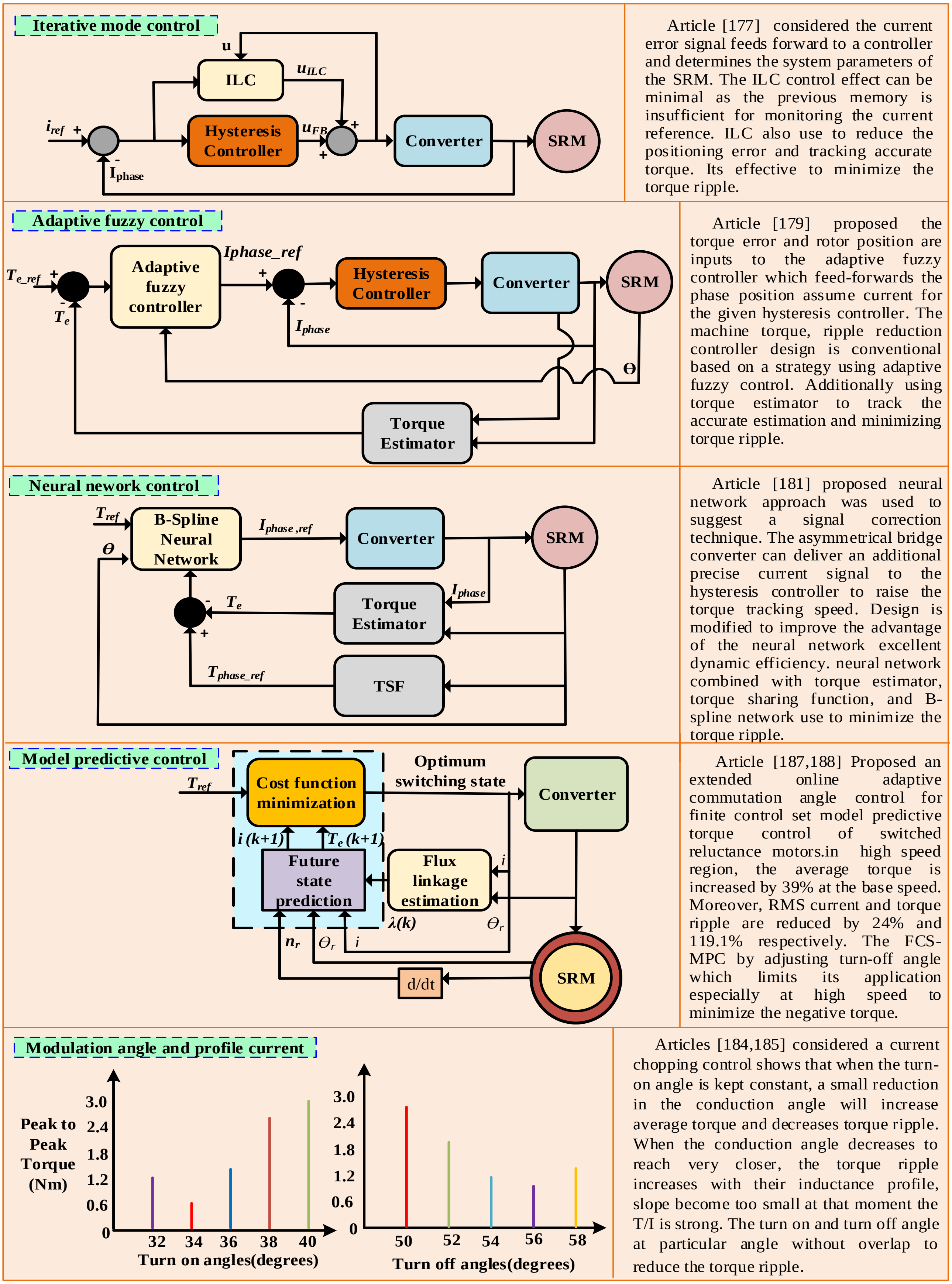

Figure 35. **Block diagram of Control techniques ILC, AFC, MPC, TSF&DITC, and MAPC.**

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Figure 36. Control techniques model equations [171,173,175,177,184,186]

TABLE XII Torque ripple reduction control techniques [13]

Control technique	Techniques adopted	Merits	Demerits	Ref
Modulation angle and profile current.	Finding the right current profiles or turn-on/off angles should be optimized.	Improved performance, increased torque-speed capability, and torque ripple decreases.	Torque and current cannot be handled flexibly, storing the current profile require large memory.	[184-186]
DTC	Using a hysteresis controller and torque calculation, control torque.	At the desired amount, direct operated instantaneous torque ripple.	Prior knowledge of system parameters is needed.	[173,174]
TSF	Implement hysteresis regulation using the torque relation current reference.	Torque is easily managed; torque waveforms can be determined and over a large speed range torque is smooth.	Offline designed torque waveforms, essential i-ɵ-t characteristics.	[171,172]
MPC	Finite control set-MPCC mathematical models predict and optimum switching states.	Intuitive, torque ripple decreases, eliminates some theoretical delay.	High precision necessitates a high sampling rate and processing power.	[173,187,188]
SMC	Integrated sliding mode control theory designed for the controller.	Anti-interference ability strong, strong robustness parameters affected less.	Design complicated controller, computing power require high value.	[175,176]
Vector control	d-q rotating frame regulates the torque.	No need for an angle decoder, since there is less torque ripple.	Complicated d-q transform.	[189]
ANN ILC FLC	Compensators or controllers built are not depending on SRM mathematical analysis using neural networks and other algorithms.	No rely on system parameters, self-learning strong, capacity adaptive strong, torque ripple reducing.	Real-time computation is complicated due to the complexity of the algorithm.	[177-182, 190]

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In [181,182] FLC technology is used to decrease torque ripple in both interior and exterior rotor SRM. The ILC control effect can be minimal as the previous memory is insufficient for monitoring the current reference. In [184,185] converter switching angle turns on/off the angle using the optimization method and modulation current profiling methods are developed for control techniques that can minimize torque ripple. The mathematical control equations of sliding mode control, model predictive control, direct torque control, fuzzy logic controller, torque sharing function, and iterative learning control are shown in Fig. 36 The advanced control techniques to mitigate torque ripple, adopted techniques, and other features are listed in Table XII.

C. SRM faults and diagnosis strategy

The SRM open circuit faults are common in the drive circuit. There are many open circuit faults such as power converter fault, winding faults, machine eccentricity fault, current sensor fault, position sensor fault and controller fault as shown in Fig. 37. However, the asymmetric half-bridge converter is important to drive SRM machines and is a more vulnerable part of the SRM drive system. In the [191] converter circuit each phase is energised independently by two switches connected in the arm bridge and providing good fault-tolerance capability. The open-circuit faults occur in the upper or lower arm device damage, the three current flows at chopping period, excitation current and demagnetization. This fault can be diagnosed based on the FFT algorithm. The SRM drive phase windings are connected series even windings and central-tapped winding comes under short circuit faults. The fault diagnosis method and fault tolerance are used to diagnose the switching device short circuits. In [192] fault part is located the corresponding fault-tolerant control strategy to diagnose the fault.

The open circuit and short circuit SRM fault diagnosis and fault tolerance strategy as shown in Fig. 38. In [193] FFT algorithm with black man window interpolation is proposed for SRM fault diagnosis with fast transients, diagnosis time within one current period, achieving fast fault detection. The developed fault diagnosis technology can achieve improve the performance of fault tolerance in SRM drive at very high temperatures, high-speed operation and safety-critical applications.

The next section discusses two different motors such as rare earth magnet BLDC hub motor and magnet less low-cost silicon SRM hub for low power rating applications of three-wheeler electric vehicles, and two-wheeler high-performance electric motor cycles.

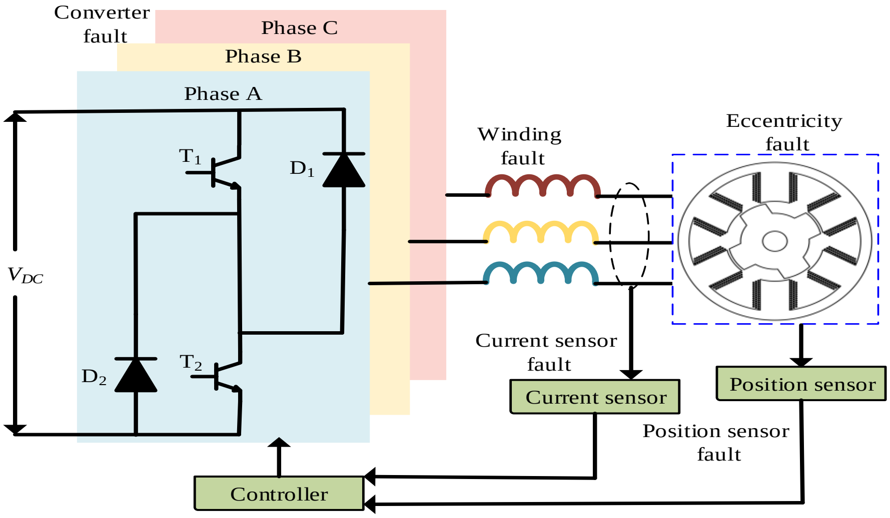

Figure 37. SRM faults in drive system

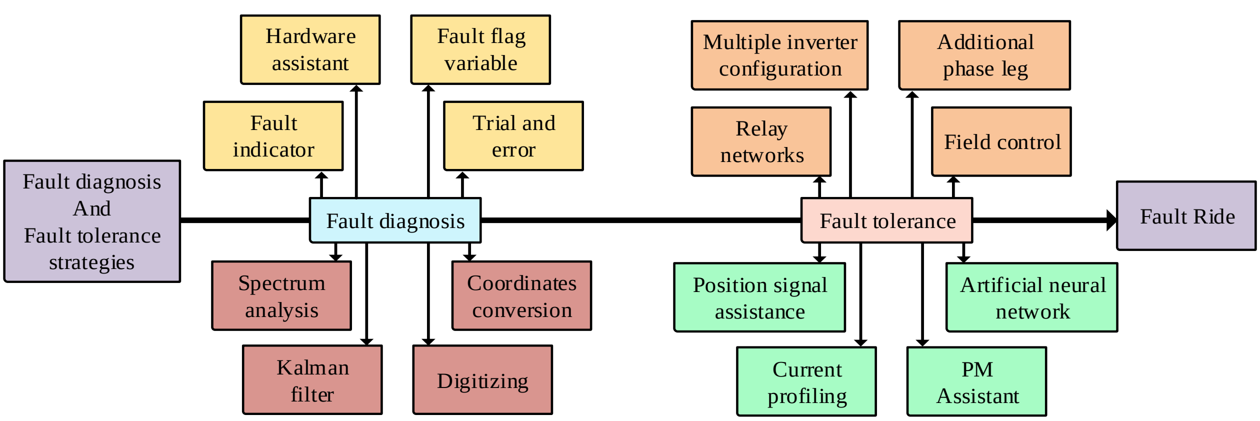

Figure 38. Fault diagonisis and fault tolerance

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VIII. BLDC AND SRM HUB MOTORS HARDWARE

According to the review offered in this article, there was much research proposed involving different control techniques such as DTC, FOC, MPC, SMC and Intelligent controller to an electric vehicle's motors. Power drivetrain's large focus on material cost, efficiency, torque ripple, noise, fault-tolerant, and losses were received a lot of attention in recent state-of-the-art research. In this purpose we have taken most promising EVs motors are rare earth magnet BLDC and magnet less SRM in-wheel for low power applications such as 2-wheeler and 3-wheeler EVs.

A. BLDC in-wheel motor analysis (Hub motor)

The BLDC in-wheel motor selected and applied different control techniques. The low power rating In-wheel BLDC motors are commercially exponential growth last few years. In [194] advantage of an In-wheel motor is no gear, no wear, no brush, controllable variable speed operation and high energy efficiency. The hardware set up with in-wheel motor and different control techniques such as FOC, DTC and intelligent control is done and results are analyzed with help of the Altair simulation software tool as shown in Fig. 39. To optimize output Multiphysics parameters, the PI-controller parameters *Kp* are changed from 0.04474 s to 0.015 ms and *Ki* to 0.04474 ms. These Altair embed results have obtained the speed of 750 rpm.

TABLE XIII **BLDC in-wheel motor specifications**

Parameters	Values
Output power	850 W
Low speed	42 km/hr.
Rated torque	14.4 Nm
Peak torque	73 Nm
Outer diameter	276.5 mm
Shaft length	276
Operating voltage	60 V
Rated current	14.8 A
Peak current	26 A
Weight	8.5 Kg

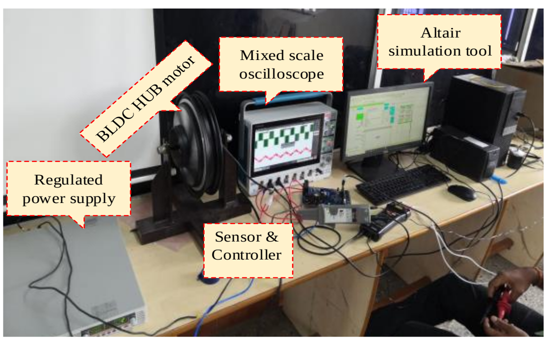

Figure 39. Hardware BLDC hub type motor setup

TABLE XIV **Motor controller parameters**

Parameters	Values
Supply voltage (V_{dc})	60 V
poles	4
Stator inductance	10.5e-3 H
Mutual inductance	1H
Stator Resistance	1.12 Ω
Current reference	0.7 A

The BLDC in-wheel motor by varying the motor speed from 500 to 1000 rpm, the motor speed at 570 rpm it reaches the maximum efficiency of 95.5% and other motor specifications are optimized and listed in Table XIII. The motor model parameters-based control parameters are listed in Table XIV.

The control techniques such as FOC, DTC, and intelligent controller applied to the in-wheel motor. The torque response in each controller as shown in Fig. 40, and Fig.41.

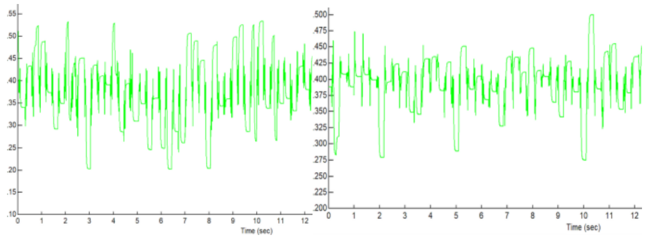

Figure 40. DTC and intelligent control torque ripple at 750 rpm

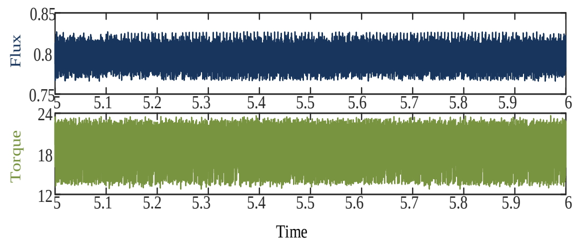

Figure 41. FOC fed torque and flux response at 750 rpm.

By verifying hardware analysis In-wheel motor control techniques such as FOC, DTC and intelligent controller. The flux ripple and torque ripple are compared.

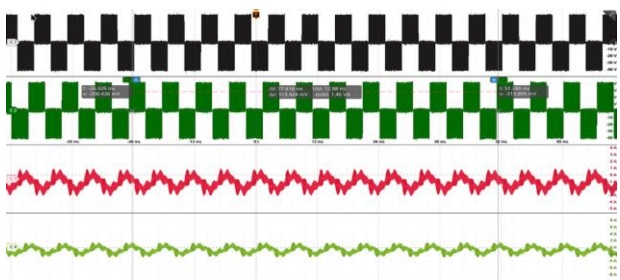

Figure 42. Phase current and line-line voltage waveform at 750 rpm

The motor back EMF phase current and THD results are obtained from the analyzed FOC topology by varying the speed of the BLDC motor at 750 rpm and shown in Fig.42 and Fig.43.

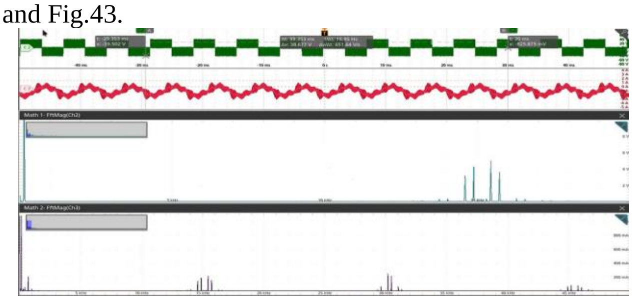

Figure 43. Current THD and Voltage THD generation

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TABLE XV Hardware results of FOC techniques

Speed	Field oriented control			
rpm	Torque ripples	Flux ripples	Current THD	Average switching frequency
750	2.165	1.951	22.35	1.812

The FOC switching states at various speed conditions are shown in Table XV. From the above results, it is inferred that the analyzed FOC technique produces minimum vector switching state transition compared to the other two methods. FOC offers to reduce torque ripple compare to DTC and intelligent controllers. From the obtained results, we can observe that the FOC control technique provides a fast dynamic response at a low speed. By experimenting sensor less with FOC, the cost and size reducing, but increase the complexity of rotor sensing information.

B. SRM motor analysis

The magnet less SRM In-wheel high speed motor selected and applied different control techniques set up as shown in Fig.44. In [195] low power rating in-wheel SRM axial flux motor not required field winding on its rotor and generates high torque density. SRM hub motor is robust motor with high fault tolerance and low production cost. It is characterized by its high-power density, high torque per ampere and wide range of speed.

TABLE XVI SRM In-wheel motor specifications

Parameters	Values
Output power	1000 W
No of teeth	16
Tooth outer diameter	24 mm
Rated torque	1.7 Nm
Peak torque	13.3 Nm
Outer diameter	153 mm
Shaft length	250
Operating voltage	60 V
Rated current	23 A
Peak current	33 A
Speed	5700 rpm
Weight	7.8 Kg

The SRM in-wheel motor by varying the motor speed from 2000 to 7000 rpm, the motor speed at 5700 rpm it reaches the maximum efficiency of 82.1 % and other motor specifications are optimized and listed in Table XVI. Based on the motor specification, the control parameters are listed in Table XVII.

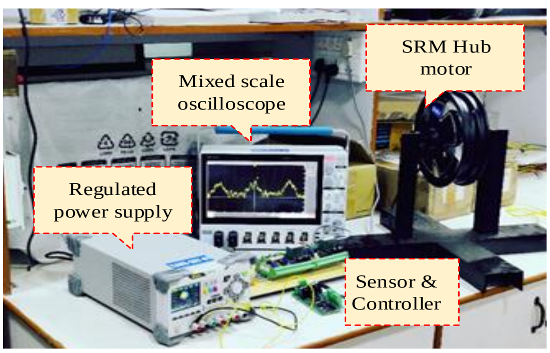

Figure 44. Hardware SRM hub type motor setup

TABLE XVII Motor controller parameters

Parameters	Values
Supply voltage (V_{dc})	60 V
Motor voltage	60 V
Aligned inductance	1.35 H
Unaligned inductance	6.5 e-3 H
Stator Resistance	0.65 Ω
Maximum flux linkage	0.97

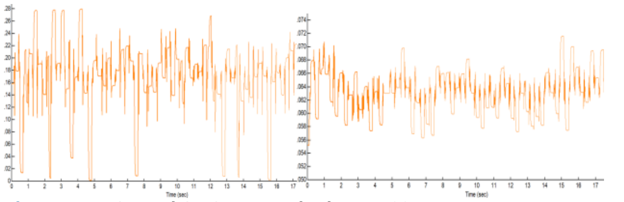

Figure 45. TSF and SMC torque ripple at 5700 rpm

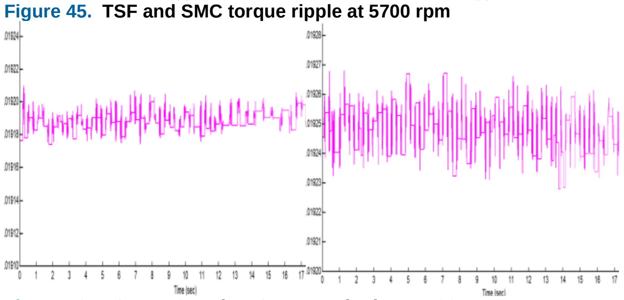

Figure 46. TSF-DITC and DTC torque ripple at 5700 rpm

We set up hardware SRM In-wheel with different control techniques such as DTC, TSF control, SMC, and TSF-based DITC using to analyses the study of torque ripple and results as shown in Fig. 45 and Fig. 46.

TABLE XVIII Peak to peak torque control at 5700 rpm

TSF	TSF-DITC	DTC	SMC
0.1925 Nm	0.01928 Nm	0.0725 Nm	0.28 Nm

Compared to four different control strategies, in that, the three control strategies TSF-DITC, DTC, and TSF have effectively reduced the torque ripple. The peak to peak torque control of all techniques is listed in Table XVIII. The SMC design controller is complicated, it requires high computing power and chatting problems. It suppresses the torque ripple value 0.28 Nm and the reference torque is set to 1 Nm. In TSF control strategy are simple torque control and this function also improve the performance of other aspects. TSF control the torque ripple suppression 0.1925 Nm.

In DTC performance, a commutation does not increase the torque ripple because switching angles are not restricted. DTC suppress the torque ripple is 0.0725 Nm, but it reduces the overall system efficiency by producing large negative torque. The combination of DITC and TSF gives better torque ripple suppression is 0.01928 Nm compared to all other control techniques, but this technique increases the control complexity. The TSF-DITC torque control calculates the reference current using reference torque and speed, to calculate the phase instant torque it requires TSC based DITC. However, these control techniques are used to suppress the torque ripple in SRM.

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IX. ELECTRIC MOTOR DESIGN (E-motor)

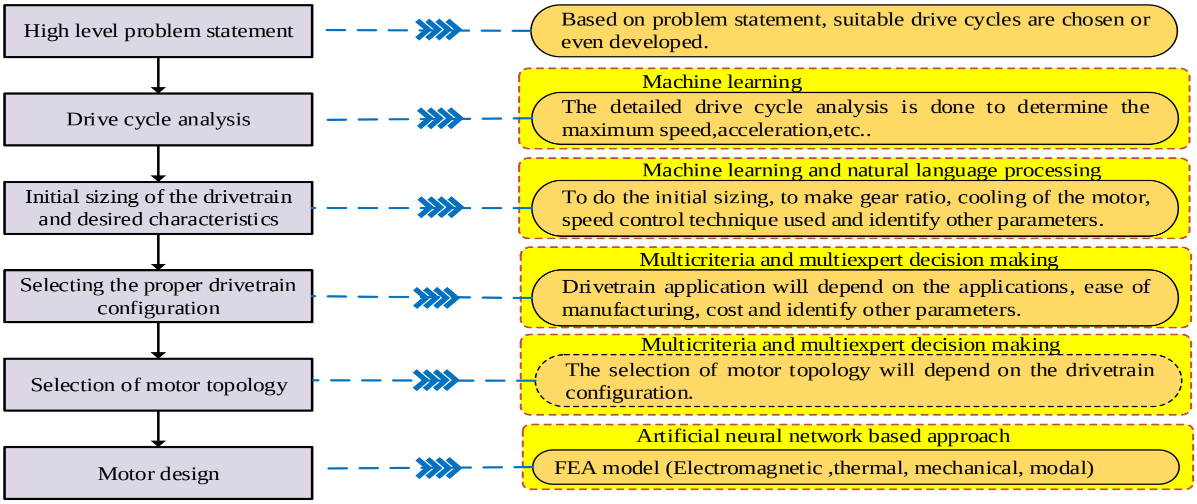

Figure 47. E-motor design flow steps

The Complete steps involved in the design of e-motor are shown in Fig.47 and 48. In [196,197] initial step of the designing process starts with a high-level problem statement based on the purpose of the vehicle to select the motor to operate at different cycles as a light-duty vehicle, medium-duty vehicle, and heavy-duty vehicle respectively. In [198] responsibility in choosing the required duty cycle to analyze the drive cycle for different driving environment road conditions to determine the speed, acceleration, power, and torque characteristics to develop the e-motor towards the next step. These characteristics are used to design powertrain e-motor initial sizing to make gear ratio, cooling of the motor, speed control techniques, and identify the other parameters using new techniques like machine learning and natural language processing. The next step is to select the proper drive train configuration to ease manufacturing, cost, high torque, and power density.

A. First stage of design

- Electro-magnetic design: Selection of motor topology, slot-pole ratio, winding layout, Stator, and rotor geometry.
- Thermal Design: Selection winding class, Varnish type, potting material selection. Design of cooling jacket based on accurate boundary conditions.
- NVH Design: Modal results simulation & Mode shapes validation for both component and assembly levels. Iterating various Slot-pole configurations to achieve an optimum Natural frequency and sound pressure levels.
- Structural Design: Analysing and optimizing stress concentration areas in various motor components. Calculation of factor of safety of various structural components and improvisation using geometry optimization.[197,198].The electrification e-motors in the market and research will emerge to develop an induction motor, IPMSM, PM assisted synchronous reluctance motors, SRM, and BLDC motors. Tuning the motor in the field weakening region. Various performance parameters are tested and validated with digital design. Optimization of digital design based on the dyno test data.

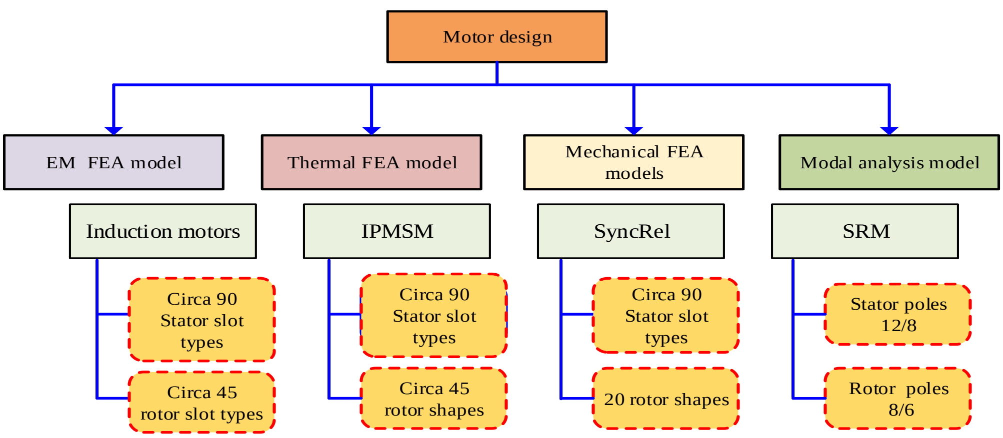

Figure 48. E- motor design FEA stages

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In [197,198] designing e-motor initially starts with the consideration of drive cycle analysis as an important aspect in the selection of motor. Drive cycle identifies the characteristics curve of motor power, speed, and torque of the vehicle. These curves are analyzed from the total tractive force acting on vehicle movement in different environment road conditions like a flat, upward, and downward. The first step involves designing the different forces acting on vehicle force in stationary, acceleration, and deacceleration mode. The important tractive force is determined from four different driving resistances acting on the vehicle which are rolling resistance force, aerodynamic drag force, grade resistance force, and acceleration force. Measurement of the power required for e-motor based on the tractive force and vehicle wheel radius is shown in Fig 49. The drive cycle plots the speed-torque characteristics for different road conditions to select a suitable e-motor for the EV powertrain.

The second step is motor specification selection on which motor is suitable to attain the duty cycle of desired speed-torque characteristics. The motor specification changes based on motor selection, here IM motor specifications are given stack length, poles, no of stator slots, rotor slot type, stator and rotor teeth flux density, air gap flux density, efficiency, and power factor. The stages start from driver duty cycle analysis, motor specifications determination, electric equivalent circuit estimation, geometric parameters estimation, magnetic model analysis, and performance evaluation as shown in Fig. 50.

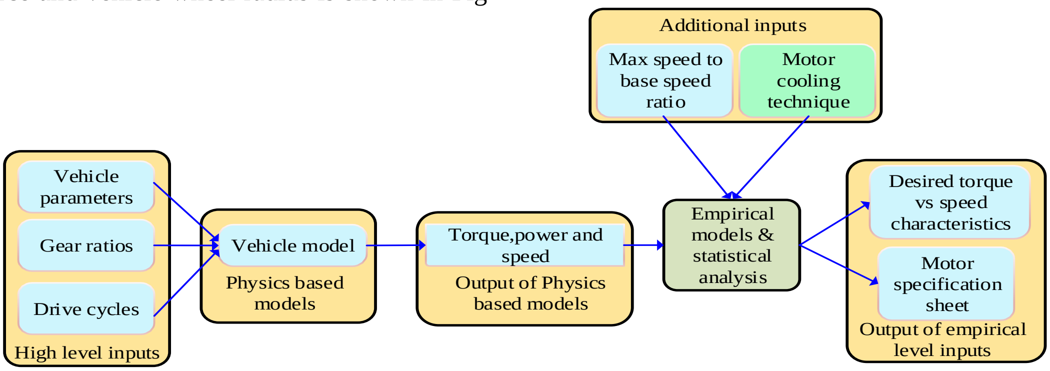

Figure 49. **E-motor first stage design**

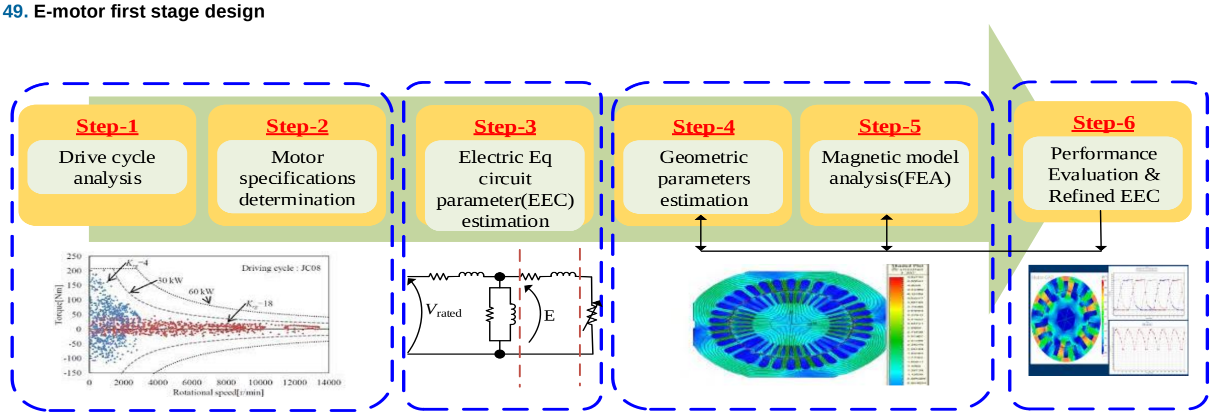

Figure 50. **E-motor design flow process**

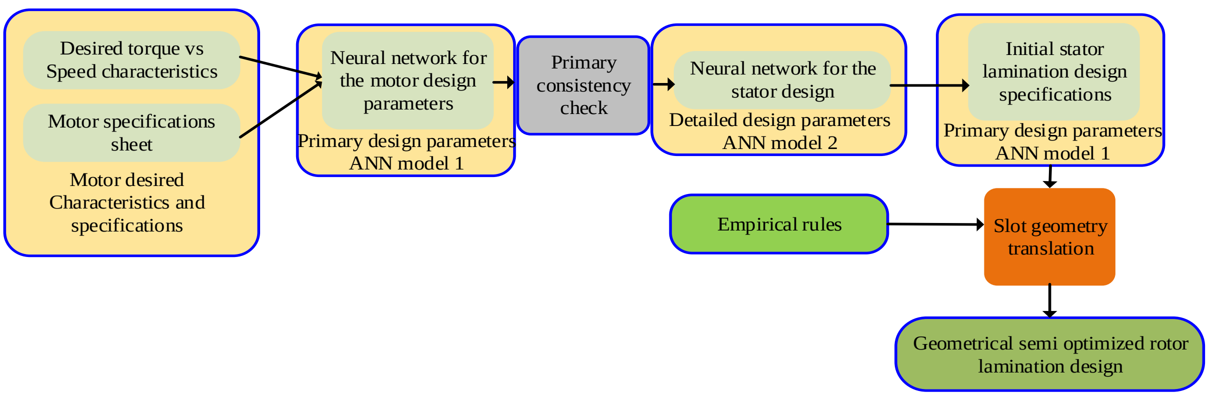

Figure 51. **E-motor stator designs**

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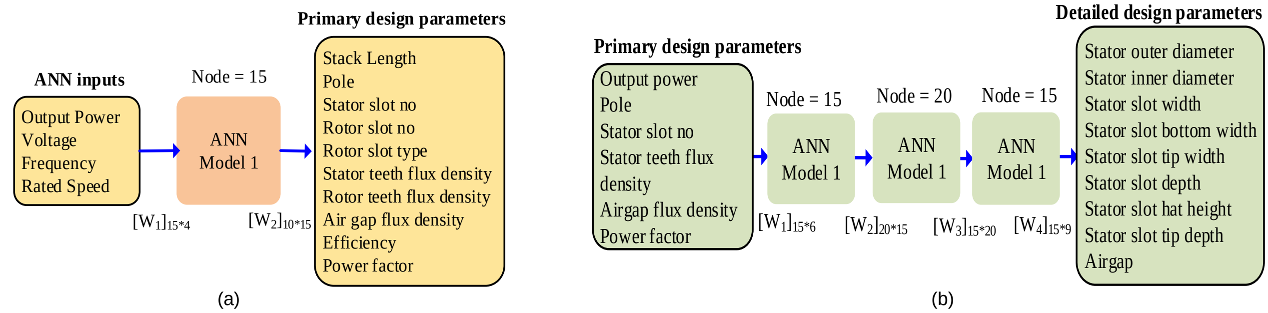

Figure 52. E-motor deign (a) ANN model 1 and (b) ANN model 2

B. Second stage of design

The FEA model output of e-motor is desired speed-torque characteristics and motor specifications taken as input for second stage motor design. Here, the four inputs such as output power, voltage, frequency, and rated speed are considered. Model 1 has taken four inputs for the neural network for the motor design parameters as shown in Fig. 51. Therefore, the ANN model 1 training set has taken 15 nodes to select important primary design parameters.

The primary consistency checks ANN have predicted is the number of stator and rotor slots based on the training data set. The improper functioning can be caused due to cogging, crawling, noisy operation, synchronous hooks, and cusp in speed-torque characteristics. ANN model 1 primary design data and ANN model 2 detailed designed data are shown in Fig. 52. The initial stator lamination design specifications satisfy the empirical rules and slot geometry translation rule. The first stage of motor design is the selection of proper function geometrical semi-optimized rotor lamination.

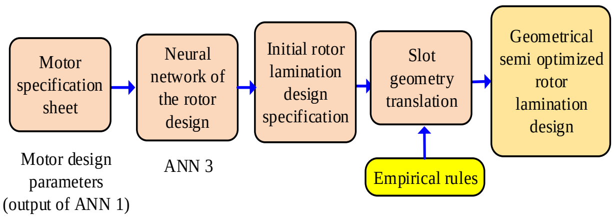

Figure 53. E-motor deign ANN model 3

Designing IM based ANN model inputs from drive duty cycle which includes output power, voltage, frequency, and rated speed. The four-input model and weights are sum in 15 node layer functioning trainset used in ANN model 1. The output primary design parameters to select proper functioning of the motor are based on the trainset function. The ANN model 3 to develop the geometrical optimized lamination deign as shown in Fig. 53.

C. Future Development

- EVs can be classified into four types HEV, PHEV, BEV, and FCEV. All these EVs are in the current trend. The lack of energy storage systems and charging stations are the main key factors to overcome BEV and PHEV in the future market. The HEV current market type is a series-parallel combination for both battery and ICE mode that comes with high efficiency and less fuel consumption, the main drawback is the cost of the vehicle. The main research on FCEV with low-cost fuel cells is most popular in military vehicles and utility vehicles.
- EVs motor can be placed with front-wheel drive, rear-wheel drive, and connect the all-wheel drive. Based on
- The drive duty cycle for vehicle application motor can be on any drive wheel. The motor that can be placed inside the wheel of the vehicle has distinct advantages. The main research is on designing motor inside wheel and control technique.
- Different types of motor used in EVs are BLDC, PMSM, IM, SRM, and SynRM. Future research in all four motors improves their drawbacks. The current trend e-motors are a combination of advantages of two different motors accounting for permanent magnet and reluctance torque.
- The BLDC motor for EVs is suitable for low-power applications such as two-wheelers and tricycles. Because of the PM interior rotor BLDC, flux density magnitude directly influences the torque and rating of the machine. The other limitation is that thermally withstanding at driving temperature condition at rotor form trapezoidal winding distribution in airgap produces more heat and creates losses. The harmonic content BLDC back EMF produces more torque ripple in EVs. While changing the speed the demagnetization effect limits the input current of BLDC in EVs. To overcome these problems the research is going on in flux concentrating type PM.
- The current trend in EVs has successfully penetrated IM which has the low-cost advantages, PM-free motor, and wider speed range. The efficiency of the motor is less compared to other motors. The regenerative braking affects the IM which has a low-efficiency influence to reduce output power and constant power range for short period. Future research to improve the efficiency of IM is by reducing the losses and increasing the power factor. The current researcher mainly focuses to reduce the core loss and resistance loss proportional to a total loss. Future IM is towards increasing the efficiency by improvement in structure design, reducing material loss. Suppressing the Fe loss technology has become good for low-cost high-performance EVs.

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- The most suitable EVs motor is internal PMSM whose high torque and high-power density proportional to high energy density non-earth material such as neodymium and samarium cobalt is too expensive is the main drawback. The future researcher is working on low-cost Ferrite PM Material to achieve high-performance EVs.
- Simple manufacturing, low-cost material SRM is suitable for EVs and is being used in the market. The main drawback for EVs is high torque ripple, low torque density, high noise, and vibration. The regenerative braking capability of SRM uses an extensive speed range, resistance to high temperatures. Future research is to improve the torque density using high saturation flux density material and motor topology developments in EVs. The future research is towards the reduction of torque ripples by the controller as well as design. Minimizing the radial force helps to reduce the acoustic noise in the SRM machine.
- The motor FEA analysis at different stages is electro-magnetic, thermal, structural, and modal analysis. The EM design is to modify the motor structure in stator and rotor teeth to improve the motor performance in the output. The thermal design improves the rotor cooling system and improves the output motor efficiency. The modal analysis reduces the acoustic noise, vibration, and harshness of the motor to improve the output torque of the motor. The structural design increases the mechanical casing rotor assembly to improve the motor power-weight ratio.
- The magnet type e-motor increases the high switching frequencies and the copper windings create skin effect problems. Based on the material laminations the eddy current loss and hysteresis loss occur to minimize the losses. The permanent magnet material containing the rotor in operation creates more eddy current losses. In high-temperature conditions, the demagnetization effect in the motor is based on material selection. The future works need to select the performance material that enables energy efficiencies such as samarium cobalt magnets and thin resistivity silicon-iron.
- The position of power and control modules within the motor assembly is done by integrated electronics to simplify the cables and connection strategy. The future integrated module needs to reduce the loss associated with cables, improve the efficiency of the machine and maximize the lifetime. In the design aspect, minimizing the cable length increases the vibration resistance.
- The sealing motor and control integrated modules with windings in the same place, subcomponent fully coated with waterproof material and properties to withstand harsh environmental particles. Future work needs to increase the lifetime of integrated subcomponents by stress in the wear of internal components.
- Thermal management is designed to improve the cooling system of the motor to minimize motor losses and improve the overall efficiency. Future work needs to improve the cooling jacket path for rotor and end windings to minimize thermal loss.

X. CONCLUSION

The electric vehicle is much needed for automotive transportation in recent days due to the most emergency created by the increase in the environmental pollution and increasing fuel cost. The rise in crude oil price in global market, high sale taxation, low availability of fossil fuels are the major reasons for drastic increase in fuel cost. The critical review in selection of motors and their control techniques for EV design to reduce torque ripple are as follows:

- PMBLDC is high-cost rare earth material, with torque ripples and reliability issues. It can be improving by using FOC, DTC, and MPC control techniques which improve the performance of high-speed efficiency, mitigating torque ripple reduction, making low-cost Fe material and increasing reliability BLDC for future EVs.
- The infrequent ground material PMSM has high torque and efficiency which gives the finest mileage but demagnetization, fault-tolerant, and cost are expensive. DTC, MPC, SMC, other intelligent control techniques improve the performance of low-cost ferrite, fault tolerance is an alternative solution of PMSM for future EVs. The design of spoke type and PMASynRM are reducing PM material to compensate for the performance and cost-effectiveness of future EVs.
- The IM is the low-cost material motor for EV choice but it produces less efficiency, more material and core losses. It can be used by DTC, FOC, and design improving efficiency techniques for long mileage IM for future EVs.
- Low-cost high core silicon material SRM limitations are average short torque density, high torque ripple, auditory noise, and vibration are created to low performance. The improving optimized design modification and TSF, DTC, TSF-DITC, SMC and other control techniques are used to increase the torque density, minimize torque ripple, reduce the auditory noise and avoid vibration of SRM for future EV.
- For in-wheel BLDC motor drive FOC techniques suppress the torque ripple compared to other techniques. Similarly, for in-wheel SRM motor drive TSF based DITC technique minimises the torque ripple in comparison with other techniques.
- The e-motor FEA design procedures and current challenges on Multiphysics simulation on EM design, thermal design, and structural design are discussed using Ansys software. The future EV could be designed with optimum-balanced solution by considering these key aspects and various other factors such as low-cost, less weight, high-power density,

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high torque density, maximum speed, high efficiency, simplicity, and long life.

Research Opportunity

- To eliminate or reduce rare earth material dependency.
- Design e-motor variation parameter for multi-objective and Multiphysics optimization on control aspects.
- Design in the wheel and central e-motor for electric traction applications.
- Improving control techniques for e-motors to minimize torque ripple, vibration, noise and improve torque density.
- Highly efficient to develop the motors with peak efficiencies of 96% and around 92% for almost the entire operational range of the vehicle.
- Development of new materials for e-motors for traction applications to improve performance and reduce cost.
- Highly Power dense and Torque Dense with a focus on achieving high torque and power density, the weight of the expensive and exotic materials used in the motor can be reduced drastically.
- Modelling, simulation, and analysis of the dynamics of e-motors for EV applications.
- To enhance the torque to magnet weight ratio through electromagnetic optimizations.
- Improving the overload capacity of e-motor for EV applications.
- To enhance the thermal capabilities of the motor which reduces the motor size/weight by incorporating multiple design techniques.
- Optimization method to design e-motor for EV applications.
- Design to minimize fault-tolerant capability for e-motors.
- Reducing high frequency switching losses, developing sensor less control, developing fault-tolerant and optimized software.
- Thermal analysis and improved cooling system methods for e-motors.
- Loss estimation and minimizing e-motor traction applications.
- EMI to be maintained according to guidelines from EMC standard IEC 610042.
- Design a compact structural packaging to improve efficiency.

APPENDIX

To construct a mathematical model for e-differential, we would need to mathematically model the kinematics of a turning vehicle. The Ackerman-Jeantaud, which encompasses all steering systems is used for this purpose. Consider the case when the EV is turning left, the radii along which the left and right wheels turn (R_r and R_l) are different. Depicts the Ackermann Jeantaud geometry. In order to minimize slipping of the wheels, the angles of the wheels while turning are also different,

$$\delta_r = arct_g \frac{L}{L/tg\delta + d/2}, \partial_l = arctg \frac{L}{L/tg\partial - d/2}$$

Where L is the wheelbase of the EV and d is the wheel track. The radius of the left and right wheels while turning,

$$R_r = L\sin^{-1}\delta_r \qquad R_l = L\sin^{-1}\delta_l$$

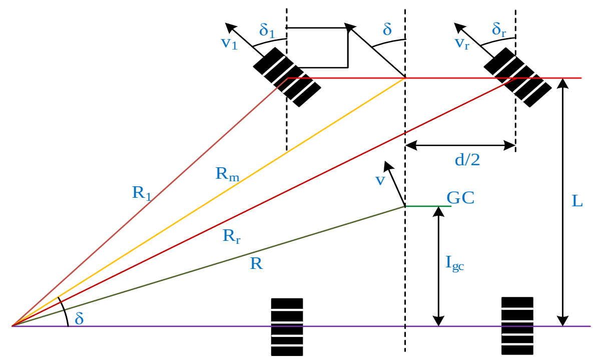

Figure 54. Ackermann Jeantaud geometry

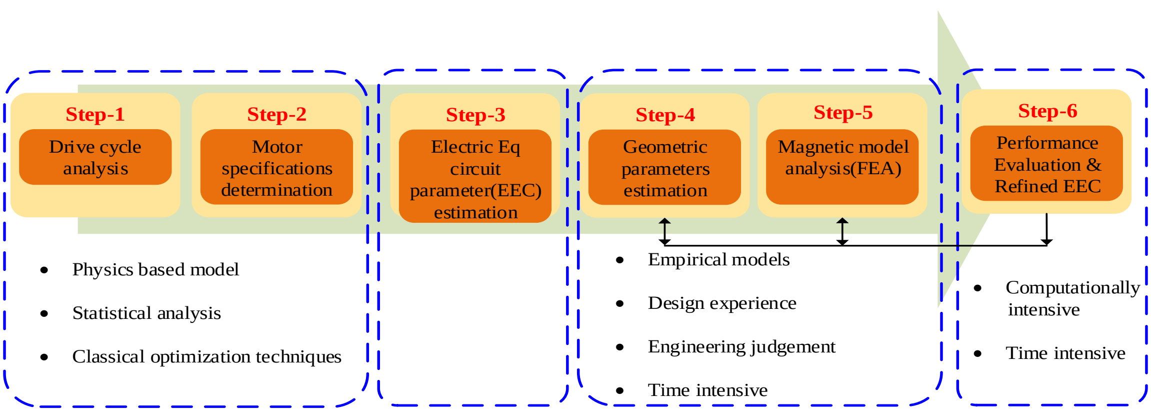

Figure 55. E-motor design challenges

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TABLE XIX Motor comparisons with different attributes

e-motors main attributes	Interior Permanent Magnet Motor (IPM)	Induction Motor (IM)	Switched Reluctance Motor (SRM)	Synchronous reluctance motor or PM reluctance (PMasyRM)
1st introduced year	1986	1889	1900	1930
Electromagnetic torque, T	$\frac{3}{2}\frac{P}{2}\{\lambda_{pm}I_{qs}-(L_{ds}-L_{qs})I_{ds}I_{qs}\}$	$\frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r}I_{ds}I_{qs}$	$\frac{1}{2}I_s^2\frac{dL(\theta)}{d\theta}$	$\frac{3}{2}\frac{P}{2}(L_{ds}-L_{qs})I_{ds}I_{qs}$
High speed suitable	0	+	++	0
Power factor, PF=	1.0	<1.0	<<1.0	$\frac{\frac{L_{ds}}{L_{qs}}-1}{\frac{L_{ds}}{L_{qs}}+1}$
Copper loss	$\frac{3}{2}R_s(I_{sd}^2+I_{sq}^2)$	$\frac{3}{2}R_s(I_{sd}^2+I_{sq}^2)+\frac{3}{2}R_r\left(\frac{L_s}{L_m}\right)I_{sq}^2$	$\frac{3}{2}R_s(I_{sd}^2+I_{sq}^2)$	$\frac{3}{2}R_s(I_{sd}^2+I_{sq}^2)$
Efficiency	++	+	+	+
Design time	++	++	+	+
Weight	+	+	+	+
cost	++	++	-	+

++ HIGH, + MEDIUM, -- LOW

TABLE XX CO_2 emission comparison between ICE and EVs

vehicles	Year and distance	Well to tank	Operation	Life cycle assessment for 1 year	Compared result	Life cycle assessment for 15 years
ICE vehicles	1 year, 10000km	0.2-ton CO_2 emission	1.5-ton CO_2 emission	1.70 -ton CO_2 emission	(1.70-0.95) EVs reducing 44% CO_2 emission in a year	25.5-ton CO_2 emission
EVs	1 year,10000km	0.95-ton CO_2 emission	Zero-ton CO_2 emission	0.95 -ton CO_2 emission		14.25-ton CO_2 emission

REFERENCES

[1] C. D. Cooper and F. C. Alley, *Air pollution control: A design approach*. Waveland press, 2010.

[2] J. J. Schauer, M. J. Kleeman, G. R. Cass, and B. R. Simoneit, "Measurement of emissions from air pollution sources. 5. C1− C32 organic compounds from gasoline-powered motor vehicles," *Environmental science & technology*, vol. 36, no. 6, pp. 1169-1180, 2002.

[3] O. A. Towoju and F. A. Ishola, "A case for the internal combustion engine powered vehicle," *Energy Reports*, vol. 6, pp. 315-321, 2020.

[4] Y. Van Fan, S. Perry, J. J. Klemeš, and C. T. Lee, "A review on air emissions assessment: Transportation," *Journal of cleaner production*, vol. 194, pp. 673-684, 2018.

[5] Y. Zhou, M. Wang, H. Hao, L. Johnson, and H. Wang, "Plug-in electric vehicle market penetration and incentives: a global review," *Mitigation and Adaptation Strategies for Global Change*, vol. 20, no. 5, pp. 777-795, 2015.

[6] R. Vidhi and P. Shrivastava, "A review of electric vehicle lifecycle emissions and policy recommendations to increase EV penetration in India," *Energies*, vol. 11, no. 3, p. 483, 2018.

[7] S. Z. Rajper and J. Albrecht, "Prospects of electric vehicles in the developing countries: a literature review," *Sustainability*, vol. 12, no. 5, p. 1906, 2020.

[8] G. L. Brase, "What would it take to get you into an electric car? Consumer perceptions and decision making about electric vehicles," *The Journal of psychology*, vol. 153, no. 2, pp. 214-236, 2019.

[9] N. Rietmann, B. Hügler, and T. Lieven, "Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions," *Journal of Cleaner Production*, vol. 261, p. 121038, 2020.

[10] D. Block, J. Harrison, P. Brooker, F. S. E. Center, and M. D. Dunn, "Electric vehicle sales for 2014 and future projections," *Electric Vehicle Transportation Center*, 2015.

[11] P. Enge, N. Enge, and S. Zoepf, *Electric Vehicle Engineering*. McGraw-Hill Education, 2021.

[12] L. Situ, "Electric vehicle development: the past, present & future," in *2009 3rd International Conference on Power Electronics Systems and Applications (PESA)*, 2009: IEEE, pp. 1-3.

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[13] Z. Wang, H. T. W. Ching, S. Huang, H. Wang, and T. Xu, "Challenges Faced by Electric Vehicle Motors and Their Solutions," *IEEE Access*, 2020.

[14] S. Madichetty, S. Mishra, and M. Basu, "New trends in electric motors and selection for electric vehicle propulsion systems," *IET Electrical Systems in Transportation*, 2020.

[15] V. Krishnan, K. Rajaram, J. Ambrose, and K. Selvam, "Comparative Analysis of Electric Motor Prototypes in the Electrical Drive Technology Applications."

[16] H.-x. Wu, S.-k. Cheng, and S.-m. Cui, "A controller of brushless DC motor for electric vehicle," *IEEE Transactions on magnetics*, vol. 41, no. 1, pp. 509-513, 2005.

[17] H. Jang, H. Kim, H.-C. Liu, H.-J. Lee, and J. Lee, “Investigation on the Torque Ripple Reduction Method of a Hybrid Electric Vehicle Motor,” *Energies*, vol. 14, no. 5, p. 1413, Mar. 2021, doi: 10.3390/en14051413.

[18] K. Kiyota and A. Chiba, "Design of switched reluctance motor competitive to 60-kW IPMSM in third-generation hybrid electric vehicle," *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2303-2309, 2012.

[19] N. Bianchi, E. Fornasiero, M. Ferrari, and M. Castiello, "Experimental comparison of PM-assisted synchronous reluctance motors," *IEEE Transactions on Industry Applications*, vol. 52, no. 1, pp. 163-171, 2015.

[20] H. Kim, Y. Park, H.-C. Liu, P.-W. Han, and J. Lee, "Study on line-start permanent magnet assistance synchronous reluctance motor for improving efficiency and power factor," *Energies*, vol. 13, no. 2, p. 384, 2020.

[21] W. Tiecheng, Z. Ping, Z. Qianfan, and C. Shukang, "Design characteristics of the induction motor used for hybrid electric vehicle," in *2004 12th Symposium on Electromagnetic Launch Technology*, 2004: IEEE, pp. 523-527.

[22] R. Thomas, H. Husson, L. Garbuio, and L. Gerbaud, "Comparative study of the Tesla Model S and Audi e-Tron Induction Motors," in *2021 17th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, 2021: IEEE, pp. 1-6.

[23] M. E. H. Benbouzid, D. Diallo and M. Zeraoulia, "Advanced Fault-Tolerant Control of Induction-Motor Drives for EV/HEV Traction Applications: From Conventional to Modern and Intelligent Control Techniques," in *IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 519-528, March 2007, doi: 10.1109/TVT.2006.889579.

[24] C. Gan, J. Wu, Q. Sun, W. Kong, H. Li, and Y. Hu, "A review on machine topologies and control techniques for low-noise switched reluctance motors in electric vehicle applications," *IEEE Access*, vol. 6, pp. 31430-31443, 2018.

[24] R. B. Inderka, M. Menne, and R. W. De Doncker, "Control of switched reluctance drives for electric vehicle applications," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 1, pp. 48-53, 2002.

[26] N. Bianchi, S. Bolognani, E. Carraro, M. Castiello, and E. Fornasiero, "Electric vehicle traction based on synchronous reluctance motors," *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 4762-4769, 2016.

[27] G. V. Kumar, C. -H. Chuang, M. -Z. Lu and C. -M. Liaw, "Development of an Electric Vehicle Synchronous Reluctance Motor Drive," in *IEEE Transactions on Vehicular Technology*, vol. 69, no. 5, pp. 5012-5024, May 2020, doi: 10.1109/TVT.2020.2983546.

[28] M. Terashima, T. Ashikaga, T. Mizuno, K. Natori, N. Fujiwara, and M. Yada, "Novel motors and controllers for high-performance electric vehicle with four in-wheel motors," *IEEE Transactions on Industrial electronics*, vol. 44, no. 1, pp. 28-38, 1997.

[29] F. Wang, Z. Zhang, X. Mei, J. Rodríguez, and R. Kennel, “Advanced Control Strategies of Induction Machine: Field Oriented Control, Direct Torque Control and Model Predictive Control,” *Energies*, vol. 11, no. 1, p. 120, Jan. 2018, doi: 10.3390/en11010120.

[30] X. Sun, T. Li, Z. Zhu, G. Lei, Y. Guo and J. Zhu, "Speed Sensorless Model Predictive Current Control Based on Finite Position Set for PMSHM Drives," in *IEEE Transactions on Transportation Electrification*, vol. 7, no. 4, pp. 2743-2752, Dec. 2021, doi: 10.1109/TTE.2021.3081436.

[31] X. Sun, T. Li, M. Yao, G. Lei, Y. Guo and J. Zhu, "Improved Finite-Control-Set Model Predictive Control with Virtual Vectors for PMSHM Drives," in *IEEE Transactions on Energy Conversion*, doi: 10.1109/TEC.2021.3138905.

[32] X. Sun, T. Li, X. Tian and J. Zhu, "Fault-Tolerant Operation of a Six-Phase Permanent Magnet Synchronous Hub Motor Based on Model Predictive Current Control With Virtual Voltage Vectors," in *IEEE Transactions on Energy Conversion*, vol. 37, no. 1, pp. 337-346, March 2022, doi: 10.1109/TEC.2021.3109869.

[33] K. Jezernik, J. Korelič and R. Horvat, "PMSM sliding mode FPGA-based control for torque ripple reduction," in *IEEE Transactions on Power Electronics*, vol. 28, no. 7, pp. 3549-3556, July 2013, doi: 10.1109/TPEL.2012.2222675.

[34] S. Nandi, H. A. Toliyat and X. Li, "Condition Monitoring and Fault Diagnosis of Electrical Motors—A Review," in *IEEE Transactions on Energy Conversion*, vol. 20, no. 4, pp. 719-729, Dec. 2005, doi: 10.1109/TEC.2005.847955.

[35] D. Xu, B. Wang, G. Zhang, G. Wang and Y. Yu, "A review of sensorless control methods for AC motor drives," in *CES Transactions on Electrical Machines*

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and Systems, vol. 2, no. 1, pp. 104-115, March 2018, doi: 10.23919/TEMS.2018.8326456.

[36] C. Chan and K. Chau, *Modern electric vehicle technology* (no. 47). Oxford University Press on Demand, 2001.

[37] E. H. Wakefield, *History of the electric automobile-hybrid electric vehicles*. 1998.

[38] M. Ehsani, K. V. Singh, H. O. Bansal, and R. T. Mehrjardi, "State of the Art and Trends in Electric and Hybrid Electric Vehicles," *Proceedings of the IEEE,* 2021.

[39] J. Guo, J. Wang, and B. Cao, "Regenerative braking strategy for electric vehicles," in *2009 IEEE Intelligent Vehicles Symposium*, 2009: IEEE, pp. 864-868.

[40] M. Elsied *et al.*, "Efficient power-electronic converters for electric vehicle applications," in *2015 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2015: IEEE, pp. 1-6.

[41] F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. N. Mollah, and E. Hossain, "A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development," *Energies,* vol. 10, no. 8, p. 1217, 2017.

[42] J. D. Widmer, R. Martin, and M. Kimiabeigi, "Electric vehicle traction motors without rare earth magnets," *Sustainable Materials and Technologies,* vol. 3, pp. 7-13, 2015.

[43] M. Zeraoulia, M. E. H. Benbouzid, and D. Diallo, "Electric motor drive selection issues for HEV propulsion systems: A comparative study," *IEEE Transactions on Vehicular technology,* vol. 55, no. 6, pp. 1756-1764, 2006.

[44] X. Zhang, D. Göhlich, and J. Li, "Energy-efficient toque allocation design of traction and regenerative braking for distributed drive electric vehicles," *IEEE Transactions on Vehicular Technology,* vol. 67, no. 1, pp. 285-295, 2017.

[45] G. Pellegrino, A. Vagati, B. Boazzo, and P. Guglielmi, "Comparison of induction and PM synchronous motor drives for EV application including design examples," *IEEE Transactions on industry applications,* vol. 48, no. 6, pp. 2322-2332, 2012.

[46] Z. Yang, F. Shang, I. P. Brown, and M. Krishnamurthy, "Comparative study of interior permanent magnet, induction, and switched reluctance motor drives for EV and HEV applications," *IEEE Transactions on Transportation Electrification,* vol. 1, no. 3, pp. 245-254, 2015.

[47] A. El-Refaie *et al.*, "Comparison of traction motors that reduce or eliminate rare-earth materials," *IET Electrical Systems in Transportation,* vol. 7, no. 3, pp. 207-214, 2017.

[48] K. Kiyota, H. Sugimoto, and A. Chiba, "Comparison of energy consumption of SRM and IPMSM in automotive driving schedules," in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2012: IEEE, pp. 853-860.

[49] B. Poudel, E. Amiri, P. Rastgoufard and B. Mirafzal, "Toward Less Rare-Earth Permanent Magnet in Electric Machines: A Review," in *IEEE Transactions on Magnetics*, vol. 57, no. 9, pp. 1-19, Sept. 2021, Art no. 900119, doi: 10.1109/TMAG.2021.3095615.

[50] Y. -H. Jung, M. -R. Park, K. -O. Kim, J. -W. Chin, J. -P. Hong and M. -S. Lim, "Design of High-Speed Multilayer IPMSM Using Ferrite PM for EV Traction Considering Mechanical and Electrical Characteristics," in *IEEE Transactions on Industry Applications*, vol. 57, no. 1, pp. 327-339, Jan.-Feb. 2021, doi: 10.1109/TIA.2020.3033783.

[51] K. Kudelina, B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste and D. V. Lukichev, "Main Faults and Diagnostic Possibilities of BLDC Motors," *2020 27th International Workshop on Electric Drives: MPEI Department of Electric Drives 90th Anniversary (IWED),* 2020, pp. 1-6, doi: 10.1109/IWED48848.2020.9069553.

[52] T.-Y. Lee, M.-K. Seo, Y.-J. Kim, and S.-Y. Jung, "Motor design and characteristics comparison of outer-rotor-type BLDC motor and BLAC motor based on numerical analysis," *IEEE Transactions on Applied Superconductivity,* vol. 26, no. 4, pp. 1-6, 2016.

[53] K. Chau, D. Zhang, J. Jiang, C. Liu, and Y. Zhang, "Design of a magnetic-geared outer-rotor permanent-magnet brushless motor for electric vehicles," *IEEE transactions on magnetics,* vol. 43, no. 6, pp. 2504-2506, 2007.

[54] G. Pellegrino, A. Vagati, P. Guglielmi, and B. Boazzo, "Performance comparison between surface-mounted and interior PM motor drives for electric vehicle application," *IEEE Transactions on Industrial Electronics,* vol. 59, no. 2, pp. 803-811, 2011.

[55] H.-x. Wu, S.-k. Cheng, and S.-m. Cui, "A controller of brushless DC motor for electric vehicle," *IEEE Transactions on magnetics,* vol. 41, no. 1, pp. 509-513, 2005.

[56] K.Vengadakrishnan, N. Madhanakkumar, P. Pugazhendiran, C. Bharatiraja, and V. Sriramkumar, "Torque ripple minimization of PMBLDC motor using simple boost inverter," *International Journal of Power Electronics and Drive Systems,* vol. 10, no. 4, p. 1714, 2019.

[57] L. Hao, M. Lin, D. Xu, N. Li, and W. Zhang, "Cogging torque reduction of axial-field flux-switching permanent magnet machine by rotor tooth notching," *IEEE Transactions on Magnetics,* vol. 51, no. 11, pp. 1-4, 2015.

[58] W. Zhao, T. A. Lipo, and B.-I. Kwon, "Torque pulsation minimization in spoke-type interior permanent magnet motors with skewing and sinusoidal permanent magnet configurations," *IEEE Transactions on Magnetics*, vol. 51, no. 11, pp. 1-4, 2015.

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[59] Z. S. Du and T. A. Lipo, "Reducing torque ripple using axial pole shaping in interior permanent magnet machines," *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 148-157, 2019.

[60] K. L. V. Iyer, C. Lai, S. Mukundan, H. Dhulipati, K. Mukherjee, and N. C. Kar, "Investigation of interior permanent magnet motor with dampers for electric vehicle propulsion and mitigation of saliency effect during integrated charging operation," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1254-1265, 2018.

[61] K.-Y. Hwang, S.-B. Rhee, B.-Y. Yang, and B.-I. Kwon, "Rotor pole design in spoke-type brushless DC motor by response surface method," *IEEE Transactions on Magnetics*, vol. 43, no. 4, pp. 1833-1836, 2007.

[62] C. Zhang and D. Bian, "A PWM control algorithm for eliminating torque ripple caused by stator magnetic field jump of brushless DC motors," in *2008 7th World Congress on Intelligent Control and Automation*, 2008: IEEE, pp. 6547-6549.

[63] J. S. Park, K. -D. Lee, S. G. Lee and W. -H. Kim, "Unbalanced ZCP Compensation Method for Position Sensorless BLDC Motor," in *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3020-3024, April 2019, doi: 10.1109/TPEL.2018.2868828.

[64] K.-Y. Nam, W.-T. Lee, C.-M. Lee, and J.-P. Hong, "Reducing torque ripple of brushless DC motor by varying input voltage," *IEEE transactions on magnetics*, vol. 42, no. 4, pp. 1307-1310, 2006.

[65] S.-I. Park, T.-S. Kim, S.-C. Ahn, and D.-S. Hyun, "An improved current control method for torque improvement of high-speed BLDC motor," in *Eighteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2003. APEC'03.*, 2003, vol. 1: IEEE, pp. 294-299.

[66] C. Chu, M.-C. Tsai, and H. Chen, "Torque control of brushless DC motors applied to electric vehicles," in *IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No. 01EX485)*, 2001: IEEE, pp. 82-87.

[67] Y. Liu, Z. Q. Zhu, and D. Howe, "Commutation-torque-ripple minimization in direct-torque-controlled PM brushless DC drives," *IEEE Transactions on Industry Applications*, vol. 43, no. 4, pp. 1012-1021, 2007.

[68] L. Romeral, A. Fabrega, J. Cusido, A. Garcia, and J. Ortega, "Torque ripple reduction in a BLDC driven by direct torque control," in *2008 IEEE Power Electronics Specialists Conference*, 2008: IEEE, pp. 4745-4751.

[69] A. M. Ajamloo, A. Ghaheri, and E. Afjei, "Multi-objective optimization of an outer rotor BLDC motor based on Taguchi method for propulsion applications," in *2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC)*, 2019: IEEE, pp. 34-39.

[70] Yoshida, Y. Murai, and M. Takada, "Noise reduction by torque ripple suppression in brushless DC motor," in *PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No. 98CH36196)*, 1998, vol. 2: IEEE, pp. 1397-1401.

[71] J.-H. Song and I. Choy, "Commutation torque ripple reduction in brushless DC motor drives using a single DC current sensor," *IEEE Transactions on Power Electronics*, vol. 19, no. 2, pp. 312-319, 2004.

[72] K. Wei, C. Hu, Z. Zhang, and Z. Lu, "A novel commutation torque ripple suppression scheme in BLDCM by sensing the DC current," in *2005 IEEE 36th Power Electronics Specialists Conference*, 2005: IEEE, pp. 1259-1263.

[73] S.-I. Park, T.-S. Kim, S.-C. Ahn, and D.-S. Hyun, "An improved current control method for torque improvement of high-speed BLDC motor," in *Eighteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2003. APEC'03.*, 2003, vol. 1: IEEE, pp. 294-299.

[74] C.-h. Wu, G.-c. Chen, and C.-b. Sun, "A wide-angle wave control method of reducing torque ripple for brushless DC motor," *Journal of Shanghai University (English Edition)*, vol. 11, no. 3, pp. 300-303, 2007.

[75] Z. Wang, S. Xie, and Z. Guo, "A complex fuzzy controller for reducing torque ripple of brushless DC motor," in *International Conference on Intelligent Computing*, 2009: Springer, pp. 804-812.

[76] M. Sumega, R. Pavol, and M. Stulrajter, "Current harmonics controller for reduction of acoustic noise, vibrations and torque ripple caused by cogging torque in BLDC motors under FOC operation." 2534. Energies 13, no. 10, 2020.

[77] S. Yaya and W. Honghua, "Research on reduction of commutation torque ripple in brushless DC motor drives based on fuzzy logic control," in 2009 International Conference on Computational Intelligence and Security, 2009, vol. 1: IEEE, pp. 240-243.

[78] K. Xia, Y. Ye, J. Ni, Y. Wang and P. Xu, "Model Predictive Control Method of Torque Ripple Reduction for BLDC Motor," in IEEE Transactions on Magnetics, vol. 56, no. 1, pp. 1-6, Jan. 2020, Art no. 7503106, Doi: 10.1109/TMAG.2019.295

[79] M. Masmoudi, B. El Badsi, and A. Masmoudi, "DTC of B4-Inverter-Fed BLDC Motor Drives with Reduced Torque Ripple During Sector-to-Sector Commutations," IEEE Transactions on Power Electronics, vol. 29, no. 9, pp. 4855–4865, Sep. 2014.

[80] M. Kimiabeigi *et al.*, "High-performance low-cost electric motor for electric vehicles using ferrite magnets,"*IEEE Transactions on Industrial Electronics*, vol. 63, no. 1, pp. 113-122, 2015.

[81] P. B. Reddy, K. Grace, and A. El-Refaie, "Conceptual design of sleeve rotor synchronous reluctance motor

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for traction applications," *IET Electric Power Applications*, vol. 10, no. 5, pp. 368-374, 2016.
[82] W. Zhao, T. A. Lipo, and B.-I. Kwon, "Comparative study on novel dual stator radial flux and axial flux permanent magnet motors with ferrite magnets for traction application," *IEEE Transactions on Magnetics*, vol. 50, no. 11, pp. 1-4, 2014.
[83] W. Zhao, T. A. Lipo, and B.-I. Kwon, "Torque pulsation minimization in spoke-type interior permanent magnet motors with skewing and sinusoidal permanent magnet configurations," *IEEE Transactions on Magnetics*, vol. 51, no. 11, pp. 1-4, 2015.
[84] T. Miura, S. Chino, M. Takemoto, S. Ogasawara, A. Chiba, and N. Hoshi, "A ferrite permanent magnet axial gap motor with segmented rotor structure for the next generation hybrid vehicle," in *The XIX International Conference on Electrical Machines-ICEM 2010*, 2010: IEEE, pp. 1-6.
[85] S. Morimoto, S. Ooi, Y. Inoue, and M. Sanada, "Experimental evaluation of a rare-earth-free PMASynRM with ferrite magnets for automotive applications," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 10, pp. 5749-5756, 2014.
[86] S. Ooi, S. Morimoto, M. Sanada, and Y. Inoue, "Performance evaluation of a high-power-density PMASynRM with ferrite magnets," *IEEE Transactions on Industry Applications*, vol. 49, no. 3, pp. 1308-1315, 2013.
[87] M. Sanada, Y. Inoue, and S. Morimoto, "Rotor structure for reducing demagnetization of magnet in a PMASynRM with ferrite permanent magnet and its characteristics," in *2011 IEEE energy conversion congress and exposition*, 2011: IEEE, pp. 4189-4194.
[88] Z. S. Du and T. A. Lipo, "Reducing torque ripple using axial pole shaping in interior permanent magnet machines," *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 148-157, 2019.
[89] R. Benlamine, F. Dubas, C. Espanet, S.-A. Randi, and D. Lhotellier, "Design of an axial-flux interior permanent-magnet synchronous motor for automotive application: Performance comparison with electric motors used in EVs and HEVs," in *2014 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2014: IEEE, pp. 1-6.
[90] Y. Chen and B. Zhang, "Minimization of the electromagnetic torque ripple caused by the coils inter-turn short circuit fault in dual-redundancy permanent magnet synchronous motors," *Energies*, vol. 10, no. 11, p. 1798, 2017.
[91] W. Kakihara, M. Takemoto, and S. Ogasawara, "Rotor structure in 50 kW spoke-type interior permanent magnet synchronous motor with ferrite permanent magnets for automotive applications," in *2013 IEEE Energy Conversion Congress and Exposition*, 2013: IEEE, pp. 606-613.
[92] M. Onsal, B. Cumhur, Y. Demir, E. Yolacan, and M. Aydin, "Rotor design optimization of a new flux-assisted consequent pole spoke-type permanent magnet torque motor for low-speed applications," *IEEE Transactions on Magnetics*, vol. 54, no. 11, pp. 1-5, 2018.
[93] M. Kimiabeigi, R. Long, J. D. Widmer, and Y. Gao, "Comparative assessment of single piece and fir-tree-based spoke type rotor designs for low-cost electric vehicle application," *IEEE Transactions on Energy Conversion*, vol. 32, no. 2, pp. 486-494, 2017.
[94] A. JABARI, M. Shakeri, and N. S. NABAVI, "Torque ripple minimization in PM synchronous motors using tooth shape optimization," 2010.
[95] G.-H. Lee, "Active cancellation of PMSM torque ripple caused by magnetic saturation for EPS applications," *Journal of Power Electronics*, vol. 10, no. 2, pp. 176-180, 2010.
[96] A. Imura, T. Takahashi, M. Fujitsuna, T. Zanma, and S. Doki, "Improved PMSM model considering flux characteristics for model predictive-based current control," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 10, no. 1, pp. 92-100, 2015.
[97] L. Romeral, A. Fabrega, J. Cusido, A. Garcia, and J. Ortega, "Torque ripple reduction in a PMSM driven by direct torque control," in *2008 IEEE Power Electronics Specialists Conference*, 2008: IEEE, pp. 4745-4751.
[98] D.-W. Chung and S.-K. Sul, "Analysis and compensation of current measurement error in vector-controlled AC motor drives," *IEEE Transactions on industry applications*, vol. 34, no. 2, pp. 340-345, 1998.
[99] Y. Zhang, W. Cao, S. McLoone and J. Morrow, "Design and Flux-Weakening Control of an Interior Permanent Magnet Synchronous Motor for Electric Vehicles," in *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 7, pp. 1-6, Oct. 2016, Art no. 0606906, doi: 10.1109/TASC.2016.2594863.
[100] J. Lara, J. Xu, and A. Chandra, "Effects of rotor position error in the performance of field-oriented-controlled PMSM drives for electric vehicle traction applications," *IEEE Transactions on Industrial electronics*, vol. 63, no. 8, pp. 4738-4751, 2016.
[101] M. M. Saafan, A. Y. Haikal, S. F. Saraya, and F. F. Areed, "Adaptive Control for Torque Ripple Minimization in PM Synchronous Motors," *International Journal of Computer Applications*, vol. 37, no. 5, pp. 1-8, 2012.
[102] H. M. Hasanien, "Torque ripple minimization of permanent magnet synchronous motor using digital observer controller," *Energy Conversion and Management*, vol. 51, no. 1, pp. 98-104, 2010.
[103] A. Piippo and J. Luomi, "Torque ripple reduction in sensorless PMSM drives," in *IECON 2006-32nd*

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Annual Conference on IEEE Industrial Electronics, 2006: IEEE, pp. 920-925.
[104] W. Qian, S. K. Panda, and J.-X. Xu, "Torque ripple minimization in PM synchronous motors using iterative learning control," *IEEE transactions on power electronics*, vol. 19, no. 2, pp. 272-279, 2004.
[105] K. Basu, J. S. Prasad, and G. Narayanan, "Minimization of torque ripple in PWM AC drives," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 2, pp. 553-558, 2008.
[106] N. Öztürk and E. Çelik, "Speed control of permanent magnet synchronous motors using fuzzy controller based on genetic algorithms," *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 889-898, 2012.
[107] M. N. Uddin, "An adaptive-filter-based torque-ripple minimization of a fuzzy-logic controller for speed control of IPM motor drives," *IEEE transactions on industry applications*, vol. 47, no. 1, pp. 350-358, 2010.
[108] G. C. Mechler, "Manufacturing and cost analysis for aluminum and copper die cast induction motors for GM's powertrain and R&D divisions," *Massachusetts Institute of Technology: Cambridge, MA, USA*, 2010.
[109] J. Kirtley, J. Cowie, E. Brush, D. Peters, and R. Kimmich, "Improving induction motor efficiency with die-cast copper rotor cages," in *2007 IEEE Power Engineering Society General Meeting*, 2007: IEEE, pp. 1-6.
[110] S. T. Varghese, K. Rajagopal, and B. Singh, "Design and development of rotor quality test system for die-cast copper rotors," *IEEE Transactions on Industry Applications*, vol. 54, no. 3, pp. 2105-2114, 2018.
[111] K. Yamazaki, "Induction motor analysis considering both harmonics and end effects using combination of 2D and 3D finite element method," *IEEE Transactions on Energy Conversion*, vol. 14, no. 3, pp. 698-703, 1999.
[112] J.-J. Lee, Y.-K. Kim, H. Nam, K.-H. Ha, J.-P. Hong, and D.-H. Hwang, "Loss distribution of three-phase induction motor fed by pulsewidth-modulated inverter," *IEEE Transactions on Magnetics*, vol. 40, no. 2, pp. 762-765, 2004.
[113] N. Stranges and R. D. Findlay, "Methods for predicting rotational iron losses in three phase induction motor stators," *IEEE transactions on magnetics*, vol. 36, no. 5, pp. 3112-3114, 2000.
[114] J. Jung and K. Nam, "A vector control scheme for EV induction motors with a series iron loss model," *IEEE transactions on industrial electronics*, vol. 45, no. 4, pp. 617-624, 1998.
[115] F. Tazerart, Z. Mokrani, D. Rekioua, and T. Rekioua, "Direct torque control implementation with losses minimization of induction motor for electric vehicle applications with high operating life of the battery," *International journal of hydrogen energy*, vol. 40, no. 39, pp. 13827-13838, 2015.
[116] A. Taheri, A. Rahmati, and S. Kaboli, "Efficiency improvement in DTC of six-phase induction machine by adaptive gradient descent of flux," *IEEE transactions on power electronics*, vol. 27, no. 3, pp. 1552-1562, 2011.
[117] T. Chelliah, J. Yadav, S. Srivastava, and P. Agarwal, "Optimal energy control of induction motor by hybridization of loss model controller based on particle swarm optimization and search controller," in *2009 World Congress on Nature & Biologically Inspired Computing (NaBIC)*, 2009: IEEE, pp. 1178-1183.
[118] S. Kaboli, M. R. Zolghadri, and E. Vahdati-Khajeh, "A fast flux search controller for DTC-based induction motor drives," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 5, pp. 2407-2416, 2007.
[119] C. Chakraborty and Y. Hori, "Fast efficiency optimization techniques for the indirect vector-controlled induction motor drives," *IEEE Transactions on Industry Applications*, vol. 39, no. 4, pp. 1070-1076, 2003.
[120] F. Farhani, A. Zaafouri, and A. Chaari, "Real time induction motor efficiency optimization," *Journal of the Franklin Institute*, vol. 354, no. 8, pp. 3289-3304, 2017.
[121] Y. Kawase, T. Yamaguchi, Z. Tu, N. Toida, N. Minoshima, and K. Hashimoto, "Effects of skew angle of rotor in squirrel-cage induction motor on torque and loss characteristics," *IEEE Transactions on Magnetics*, vol. 45, no. 3, pp. 1700-1703, 2009.
[122] Q. Zhang, H. Liu, Z. Zhang, and T. Song, "A cast copper rotor induction motor for small commercial EV traction: Electromagnetic design, analysis, and experimental tests," *CES Transactions on Electrical Machines and Systems*, vol. 2, no. 4, pp. 417-424, 2018.
[123] G. Lee, S. Min, and J.-P. Hong, "Optimal shape design of rotor slot in squirrel-cage induction motor considering torque characteristics," *IEEE Transactions on Magnetics*, vol. 49, no. 5, pp. 2197-2200, 2013.
[124] D. Zhang, C. S. Park, and C. S. Koh, "A new optimal design method of rotor slot of three-phase squirrel cage induction motor for NEMA class D speed-torque characteristic using multi-objective optimization algorithm," *IEEE transactions on magnetics*, vol. 48, no. 2, pp. 879-882, 2012.
[125] M. J. Akhtar and R. K. Behera, "Optimal design of stator and rotor slot of induction motor for electric vehicle applications," *IET Electrical Systems in Transportation*, vol. 9, no. 1, pp. 35-43, 2019.
[126] M. Hajian, J. Soltani, G. A. Markadeh, and S. Hosseinnia, "Adaptive nonlinear direct torque control of sensorless IM drives with efficiency optimization," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 3, pp. 975-985, 2009.

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[127] J. R. Dominguez, C. Mora-Soto, S. Ortega-Cisneros, J. J. R. Panduro, and A. G. Loukianov, "Copper and core loss minimization for induction motors using high-order sliding-mode control," *IEEE transactions on Industrial Electronics*, vol. 59, no. 7, pp. 2877-2889, 2011.
[128] L. Alberti, N. Bianchi, A. Boglietti, and A. Cavagnino, "Core axial lengthening as effective solution to improve the induction motor efficiency classes," *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 218-225, 2013.
[129] D. Lindenmeyer, H. Dommel, A. Moshref, and P. Kundur, "An induction motor parameter estimation method," *International journal of electrical power & energy systems*, vol. 23, no. 4, pp. 251-262, 2001.
[130] D. Gerada, A. Mebarki, N. L. Brown, K. J. Bradley, and C. Gerada, "Design aspects of high-speed high-power-density laminated-rotor induction machines," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 4039-4047, 2010.
[131] K. M. Rahman and S. E. Schulz, "Design of high-efficiency and high-torque-density switched reluctance motor for vehicle propulsion," *IEEE Transactions on Industry Applications*, vol. 38, no. 6, pp. 1500-1507, 2002.
[132] H. Goto, S. Murakami, and O. Ichinokura, "Design to maximize torque-volume density of axial-flux SRM for in-wheel EV," in *IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society*, 2015: IEEE, pp. 005191-005196.
[133] S. Murakami, H. Goto, and O. Ichinokura, "A study about optimum stator pole design of axial-gap switched reluctance motor," in *2014 International Conference on Electrical Machines (ICEM)*, 2014: IEEE, pp. 975-980.
[134] A. Chiba *et al.*, "Torque density and efficiency improvements of a switched reluctance motor without rare-earth material for hybrid vehicles," *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1240-1246, 2011.
[135] M. Takeno, A. Chiba, N. Hoshi, S. Ogasawara, M. Takemoto, and M. A. Rahman, "Test results and torque improvement of the 50-kW switched reluctance motor designed for hybrid electric vehicles," *IEEE Transactions on Industry Applications*, vol. 48, no. 4, pp. 1327-1334, 2012.
[136] Y. Zhu, W. Wei, C. Yang, and Y. Zhang, "Multi-objective optimisation design of two-phase excitation switched reluctance motor for electric vehicles," *IET Electric Power Applications*, vol. 12, no. 7, pp. 929-937, 2018.
[137] T. Boukhobza, M. Gabsi, and B. Grioni, "Random variation of control angles, reduction of SRM vibrations," in *IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No. 01EX485)*, 2001: IEEE, pp. 640-643.
[138] M. Abbasian, M. Moallem, and B. Fahimi, "Double-stator switched reluctance machines (DSSRM): Fundamentals and magnetic force analysis," *IEEE Transactions on energy conversion*, vol. 25, no. 3, pp. 589-597, 2010.
[139] H.-Y. Yang, Y.-C. Lim, and H.-C. Kim, "Acoustic noise/vibration reduction of a single-phase SRM using skewed stator and rotor," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 10, pp. 4292-4300, 2012.
[140] K. Kiyota, T. Kakishima, A. Chiba, and M. A. Rahman, "Cylindrical rotor design for acoustic noise and windage loss reduction in switched reluctance motor for HEV applications," *IEEE Transactions on Industry Applications*, vol. 52, no. 1, pp. 154-162, 2015.
[141] X.-q. Guo, R. Zhong, D.-s. Ding, M.-s. Zhang, W.-j. Shao, and W.-f. Sun, "Origin of resonance noise and analysis of randomising turn-on angle method in switched reluctance motor," *IET Electric Power Applications*, vol. 11, no. 7, pp. 1324-1332, 2017.
[142] P. O. Rasmussen, J. H. Andreasen, and J. M. Pijanowski, "Structural stator spacers-a solution for noise reduction of switched reluctance motors," *IEEE Transactions on Industry Applications*, vol. 40, no. 2, pp. 574-581, 2004.
[143] A. H. Isfahani and B. Fahimi, "Comparison of mechanical vibration between a double-stator switched reluctance machine and a conventional switched reluctance machine," *IEEE Transactions on Magnetics*, vol. 50, no. 2, pp. 293-296, 2014.
[144] Y. Zou, K.-W. E. Cheng, N. C. Cheung, and J. Pan, "Deformation and noise mitigation for the linear switched reluctance motor with skewed teeth structure," *IEEE Transactions on Magnetics*, vol. 50, no. 11, pp. 1-4, 2014.
[145] J. Chai, Y. Lin, and C. Liaw, "Comparative study of switching controls in vibration and acoustic noise reductions for switched reluctance motor," *IEE Proceedings-Electric Power Applications*, vol. 153, no. 3, pp. 348-360, 2006.
[146] X. Cao, Z. Deng, G. Yang, and X. Wang, "Independent control of average torque and radial force in bearingless switched-reluctance motors with hybrid excitations," *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1376-1385, 2009.
[147] J.-W. Ahn, S.-J. Park, and D.-H. Lee, "Hybrid excitation of SRM for reduction of vibration and acoustic noise," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 2, pp. 374-380, 2004.
[148] M. Takiguchi, H. Sugimoto, N. Kurihara, and A. Chiba, "Acoustic noise and vibration reduction of SRM by elimination of third harmonic component in sum of radial forces," *IEEE Transactions on Energy Conversion*, vol. 30, no. 3, pp. 883-891, 2015.
[149] C. Pollock and C.-Y. Wu, "Acoustic noise cancellation techniques for switched reluctance

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drives," *IEEE transactions on industry applications*, vol. 33, no. 2, pp. 477-484, 1997.

[150] H. Makino, T. Kosaka, and N. Matsui, "Digital PWM-control-based active vibration cancellation for switched reluctance motors," *IEEE Transactions on Industry applications*, vol. 51, no. 6, pp. 4521-4530, 2015.

[151] A. Rezig, W. Boudendouna, A. Djerdir, and A. N'Diaye, "Investigation of optimal control for vibration and noise reduction in-wheel switched reluctance motor used in electric vehicle," *Mathematics and Computers in Simulation*, vol. 167, pp. 267-280, 2020.

[152] C. Gan, J. Wu, M. Shen, S. Yang, Y. Hu, and W. Cao, "Investigation of skewing effects on the vibration reduction of three-phase switched reluctance motors," *IEEE Transactions on Magnetics*, vol. 51, no. 9, pp. 1-9, 2015.

[153] F.-C. Lin and S.-M. Yang, "Instantaneous shaft radial force control with sinusoidal excitations for switched reluctance motors," *IEEE Transactions on Energy Conversion*, vol. 22, no. 3, pp. 629-636, 2007.

[154] X.-q. Guo, R. Zhong, D.-s. Ding, M.-s. Zhang, W.-j. Shao, and W.-f. Sun, "Origin of resonance noise and analysis of randomising turn-on angle method in switched reluctance motor," *IET Electric Power Applications*, vol. 11, no. 7, pp. 1324-1332, 2017.

[155] X. Guo, R. Zhong, M. Zhang, D. Ding, and W. Sun, "Resonance reduction by optimal switch angle selection in switched reluctance motor," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 3, pp. 1867-1877, 2019.

[156] P. C. Desai, M. Krishnamurthy, N. Schofield, and A. Emadi, "Novel switched reluctance machine configuration with higher number of rotor poles than stator poles: Concept to implementation," *IEEE Transactions on industrial electronics*, vol. 57, no. 2, pp. 649-659, 2009.

[157] B. Bilgin, A. Emadi, and M. Krishnamurthy, "Design considerations for switched reluctance machines with a higher number of rotor poles," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 10, pp. 3745-3756, 2011.

[158] M. Deepak , G.Janaki, C. Bharatiraja, "Power electronic converter topologies for switched reluctance motor towards torque ripple analysis" *Materials Today: Proceedings*. 2022 Jan 1;52:1657-65.

[159] J. W. Lee, H. S. Kim, B. I. Kwon, and B. T. Kim, "New rotor shape design for minimum torque ripple of SRM using FEM," *IEEE transactions on magnetics*, vol. 40, no. 2, pp. 754-757, 2004.

[160] X. Liu and Z. Zhu, "Stator/rotor pole combinations and winding configurations of variable flux reluctance machines," *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3675-3684, 2014.

[161] N. Sheth and K. Rajagopal, "Optimum pole arcs for a switched reluctance motor for higher torque with reduced ripple," *IEEE Transactions on Magnetics*, vol. 39, no. 5, pp. 3214-3216, 2003.

[162] A. Seshadri and N. C. Lenin, "Review based on losses, torque ripple, vibration and noise in switched reluctance motor," *IET Electric Power Applications*, vol. 14, no. 8, pp. 1311-1326, 2020.

[163] M. Balaji and V. Kamaraj, "Evolutionary computation based multi-objective pole shape optimization of switched reluctance machine," *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 63-69, 2012.

[164] D.-H. Lee, J. Liang, Z.-G. Lee, and J.-W. Ahn, "A simple nonlinear logical torque sharing function for low-torque ripple SR drive," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 8, pp. 3021-3028, 2009.

[165] X. Ai-de, Z. Xianchao, H. Kunlun, and C. Yuzhao, "Torque-ripple reduction of SRM using optimised voltage vector in DTC," *IET Electrical Systems in Transportation*, vol. 8, no. 1, pp. 35-43, 2018.

[166] N. Yan, X. Cao, and Z. Deng, "Direct torque control for switched reluctance motor to obtain high torque–ampere ratio," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5144-5152, 2018.

[167] R. Mikail, I. Husain, Y. Sozer, M. S. Islam, and T. Sebastian, "A fixed switching frequency predictive current control method for switched reluctance machines," *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3717-3726, 2014.

[168] J. Ye, P. Malysz, and A. Emadi, "A fixed-switching-frequency integral sliding mode current controller for switched reluctance motor drives," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 2, pp. 381-394, 2014.

[169] N. Nakao and K. Akatsu, "Vector control specialized for switched reluctance motor drives," *Electrical Engineering in Japan*, vol. 194, no. 2, pp. 24-36, 2016.

[170] L. O. Henriques, L. G. Rolim, W. I. Suemitsu, P. J. Branco, and J. A. Dente, "Torque ripple minimization in a switched reluctance drive by neuro-fuzzy compensation," *IEEE Transactions on magnetics*, vol. 36, no. 5, pp. 3592-3594, 2000.

[171] X. Xue, K. W. E. Cheng, and S. L. Ho, "Optimization and evaluation of torque-sharing functions for torque ripple minimization in switched reluctance motor drives," *IEEE transactions on power electronics*, vol. 24, no. 9, pp. 2076-2090, 2009.

[172] C. Choi, S. Kim, Y. Kim, and K. Park, "A new torque control method of a switched reluctance motor using a torque-sharing function," *IEEE Transactions on Magnetics*, vol. 38, no. 5, pp. 3288-3290, 2002.

[173] A. Xu, C. Shang, J. Chen, J. Zhu, and L. Han, "A new control method based on DTC and MPC to reduce torque ripple in SRM," *IEEE Access*, vol. 7, pp. 68584-68593, 2019.

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[174] N. H. Fuengwarodsakul, M. Menne, R. B. Inderka, and R. W. De Doncker, "High-dynamic four-quadrant switched reluctance drive based on DITC," *IEEE transactions On Industry applications*, vol. 41, no. 5, pp. 1232-1242, 2005.
[175] N. Inanc and V. Ozbulur, "Torque ripple minimization of a switched reluctance motor by using continuous sliding mode control technique," *Electric Power Systems Research*, vol. 66, no. 3, pp. 241-251, 2003.
[176] W. Shang, S. Zhao, Y. Shen, and Z. Qi, "A sliding mode flux-linkage controller with integral compensation for switched reluctance motor," *IEEE Transactions on Magnetics*, vol. 45, no. 9, pp. 3322-3328, 2009.
[177] S. K. Sahoo, S. K. Panda, and J.-X. Xu, "Iterative learning-based high-performance current controller for switched reluctance motors," *IEEE Transactions on Energy Conversion*, vol. 19, no. 3, pp. 491-498, 2004.
[178] S. K. Sahoo, S. K. Panda, and J.-X. Xu, "Indirect torque control of switched reluctance motors using iterative learning control," *IEEE Transactions on Power Electronics*, vol. 20, no. 1, pp. 200-208, 2005.
[179] S. Mir, M. S. Islam, T. Sebastian, and I. Husain, "Fault-tolerant switched reluctance motor drive using adaptive fuzzy logic controller," *IEEE Transactions on Power Electronics*, vol. 19, no. 2, pp. 289-295, 2004.
[180] M. Divandari and A. Dadpour, "Radial force and torque ripple optimization for acoustic noise reduction of SRM drives via fuzzy logic control," in *2010 9th IEEE/IAS International Conference on Industry Applications-INDUSCON 2010*, 2010: IEEE, pp. 1-6.
[181] Z. Lin, D. S. Reay, B. W. Williams, and X. He, "Torque ripple reduction in switched reluctance motor drives using B-spline neural networks," *IEEE Transactions on Industry Applications*, vol. 42, no. 6, pp. 1445-1453, 2006.
[182] S. Masoudi, M. R. Soltanpour, and H. Abdollahi, "Adaptive fuzzy control method for a linear switched reluctance motor," *IET Electric Power Applications*, vol. 12, no. 9, pp. 1328-1336, 2018.
[183] C Gan, J Wu, Q Sun,S Yang, Y Hu, and L Jin, "Low-cost direct instantaneous torque control for switched reluctance motors with bus current detection under soft-chopping mode. *IET Power Electronics*, *9*(3), pp.482-490,2016.
[184] C. Mademlis and I. Kioskeridis, "Performance optimization in switched reluctance motor drives with online commutation angle control," *IEEE Transactions on Energy Conversion*, vol. 18, no. 3, pp. 448-457, 2003.
[185] N. T. Shaked and R. Rabinovici, "New procedures for minimizing the torque ripple in switched reluctance motors by optimizing the phase-current profile," *IEEE Transactions on magnetics*, vol. 41, no. 3, pp. 1184-1192, 2005.
[186] R. Mikail, I. Husain, Y. Sozer, M. S. Islam, and T. Sebastian, "Torque-ripple minimization of switched reluctance machines through current profiling," *IEEE Transactions on Industry Applications*, vol. 49, no. 3, pp. 1258-1267, 2013.
[187] J. Villegas, S. Vazquez, J. Carrasco, and I. Gil, "Model predictive control of a switched reluctance machine using discrete space vector modulation," in *2010 IEEE International Symposium on Industrial Electronics*, 2010: IEEE, pp. 3139-3144.
[188] C. Li, G. Wang, Y. Li, and A. Xu, "An improved finite-state predictive torque control for switched reluctance motor drive," *IET Electric Power Applications*, vol. 12, no. 1, pp. 144-151, 2018.
[189] I. Husain, "Minimization of torque ripple in SRM drives," *IEEE transactions on Industrial Electronics*, vol. 49, no. 1, pp. 28-39, 2002.
[190] L. Kalaivani, N. Marimuthu, and P. Subburaj, "Intelligent control for torque-ripple minimization in switched reluctance motor," in *2011 1st International Conference on Electrical Energy Systems*, 2011: IEEE, pp. 182-186.
[[191] K. -J. Lee, N. -J. Park, K. -H. Kim and D. -S. Hyun, "Simple fault detection and tolerant scheme in VSI-fed switched reluctance motor," *2006 37th IEEE Power Electronics Specialists Conference*, 2006, pp. 1-6, doi: 10.1109/pesc.2006.1712238.Z. Gao, C. Cecati and S. X. Ding, "A Survey of Fault Diagnosis and Fault-Tolerant Techniques—Part I: Fault Diagnosis With Model-Based and Signal-Based Approaches," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 6, pp. 3757-3767, June 2015, doi: 10.1109/TIE.2015.2417501.
[192] H. -S. Ro, D. -H. Kim, H. -G. Jeong and K. -B. Lee, "Tolerant Control for Power Transistor Faults in Switched Reluctance Motor Drives," in *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 3187-3197, July-Aug. 2015, doi: 10.1109/TIA.2015.2411662.
[193] J. Ye, B. Bilgin, and A. Emadi, "An extended-speed low-ripple torque control of switched reluctance motor drives," *IEEE Transactions on Power Electronics*, vol. 30, no. 3, pp. 1457-1470, 2014.
[194] K. L. Butler, M. Ehsani, and P. Kamath, "A Matlab-based modeling and simulation package for electric and hybrid electric vehicle design," *IEEE Transactions on vehicular technology*, vol. 48, no. 6, pp. 1770-1778, 1999.
[195] Z. Yueying, Y. Chuantian, Y. Yuan, W. Weiyan, and Z. Chengwen, "Design and optimisation of an In-wheel switched reluctance motor for electric vehicles," *IET Intelligent Transport Systems*, vol. 13, no. 1, pp. 175-182, 2019.
[196] Z. Shi, X. Sun, Y. Cai, X. Tian, and L. Chen, "Design optimisation of an outer-rotor permanent magnet synchronous hub motor for a low-speed campus patrol

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EV," *IET Electric Power Applications*, vol. 14, no. 11, pp. 2111-2118, 2020.

[197] M. Ikeda and T. Hiyama, "ANN based designing and cost determination system for induction motor," *IEE Proceedings-Electric Power Applications*, vol. 152, no. 6, pp. 1595-1602, 2005.

[198] J. A. Makwana, P. Agarwal, and S. Srivastava, "ANN based sensorless rotor position estimation for the Switched Reluctance Motor," in *2011 Nirma University International Conference on Engineering*, 2011: IEEE, pp. 1-6.

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