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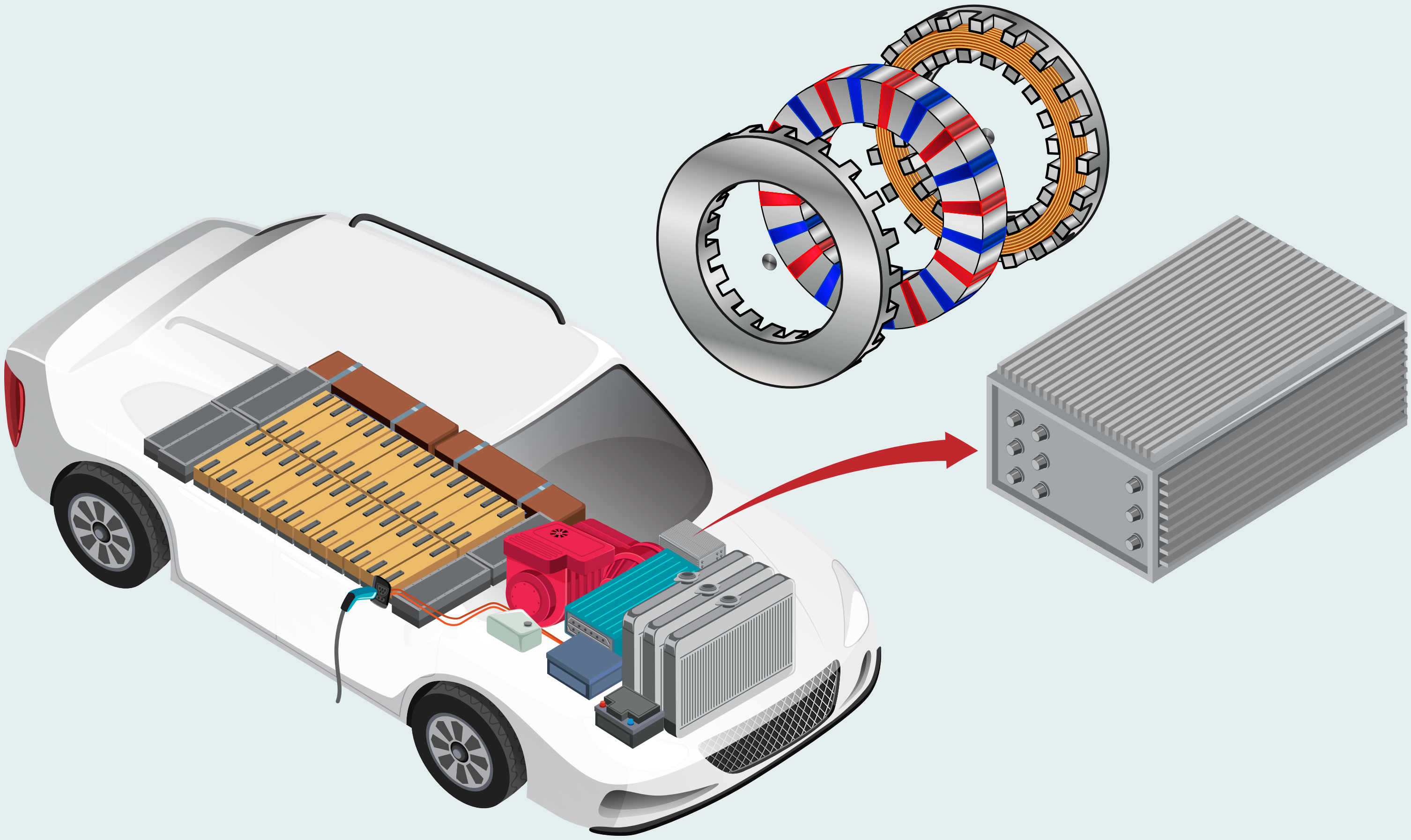
R&D Roadmap on

Power Electronics, Machines and Drives

TECHNOLOGIES TO OVERCOME HINDRANCES TO E-MOBILITY



VOLUME No. 2

R&D Roadmap on

Power Electronics, Machines and Drives

TECHNOLOGIES TO OVERCOME HINDRANCES TO E-MOBILITY

[Note: Thematic report based on DST's White Paper on Catalysing Technology-Led Ecosystem for e-Mobility].

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सत्यमेव जयते
प्रो. अभय करंदीकर
Prof. Abhay Karandikar

सचिव
भारत सरकार
विज्ञान एवं प्रौद्योगिकी मंत्रालय
विज्ञान एवं प्रौद्योगिकी विभाग
Secretary
Government of India
Ministry of Science and Technology
Department of Science and Technology

17th October, 2024

MESSAGE

India's commitment to achieve a Net-Zero emission target by 2070 and reducing carbon emissions by one billion tonnes by 2030 underscores the critical need for a transition to electric mobility. India aims to achieve 30% EV market share by 2030. Spurred by encouraging initiatives by the Government of India, EV industry is growing at faster pace and automotive industry is gearing up to ramp up their operations to meet domestic demand. Many innovative start-ups have also ventured into this domain.

While there is significant growth in this sector, there are still many challenges that needs to be addressed for effective EV adoption in the country. At present, the industry depends heavily on imported materials/components due to lack of domestic supply chain and manufacturing capabilities in the country. This calls for a strategy and intervention in developing indigenous R&D capabilities to strengthen the capacity and capability of Industry for long term sustainability and end-to-end value creation across the value chain.

In this context, the Department of Science and Technology (DST) has prepared EV R&D Roadmaps to assess existing technology gaps and propose viable solutions. These documents aim to establish an industry-focused R&D roadmap for the development of indigenous components, processes, and technologies that will benefit the sector. Two year-long intensive consultation process involving over 200 stakeholders has culminated in these R&D Roadmaps, which focus on Tropical EV Batteries, Power Electronics, Machines and Drives and EV Charging Infrastructure.

With the establishment of the Anushandhan National Research Foundation (ANRF), DST is well-positioned to concentrate on clean energy and decarbonization pathways, under EV Mission, which has been recently launched, guiding India's energy transition and working towards the goal of Net Zero by 2070.

I would like to commend the DST team for their tremendous efforts and acknowledge the invaluable contributions of domain experts from academia, industry, and ecosystem partners in producing these crucial insights for e-Mobility.

I am confident that this document will serve as an important reference guide for the R&D community and will drive new advancements in industry-oriented R&D initiatives for e-Mobility in India.

(Abhay Karandikar)

Technology Bhavan, New Mehrauli Road, New Delhi - 110016
Tel: +91 11 26511439 / 26510068 | Fax: + 91 11 26863847 | e-mail: dstsec@nic.in | website: www.dst.gov.in

सत्यमेव जयते
डा. अनिता गुप्ता
Dr. Anita Gupta

सलाहकार एवं प्रमुख/वैज्ञानिक 'जी'
जलवायु, ऊर्जा व सतत् तकनीक
विज्ञान और प्रौद्योगिकी विभाग
भारत सरकार
ADVISOR & HEAD / SCIENTIST 'G'
Climate, Energy and
Sustainable Technology (CEST)
Department of Science & Technology
Government of India

MESSAGE

In the effort to decarbonise India, the mobility sector is undergoing significant transformation, with Electric Vehicles at the forefront as a sustainable solution for the future. India aspires to become a global manufacturing hub for electric vehicles.

To achieve this ambitious goal and foster an environment conducive to innovation, Department of Science and Technology (DST) had launched a pioneering initiative to prepare R&D Roadmaps on three key areas: Tropical EV Batteries, EV Power Electronics and Machine and Drives and EV Charging Infrastructure. These documents analysed current capabilities, identify gaps and challenges and proposed actionable strategies to accelerate advancement in indigenous technologies while building a robust R&D and manufacturing eco system.

A key focus is establishing self-reliant battery ecosystem which include setting up of pilot production facilities for battery cell manufacturing. In case of power electronics and machine drives, it is envisaged to develop market driven products through creation of Centres of Excellence (CoEs). These R&D Roadmaps also address supply chain challenges related to essential materials like lithium salts and rare earth oxides under scoring the need for standardized processing technologies to support extraction, product development and recycling of end-of-life products. Further, low cost, innovative solutions have been proposed to enhance the ease of doing business in EV charging infrastructure sector.

I would like to extend my heartfelt thanks to the Advisory Committee led by Prof. B.G. Fernandes from IIT Bombay, and to the expert members for their invaluable contributions in crafting these R&D Roadmaps with high quality content, in-depth analysis and actionable framework. Lastly, I appreciate the efforts of my colleague, Mr. Suresh Babu Muttana, Scientist-E, DST in engaging with industry experts and stakeholders which has resulted in rich insights that shaped these R&D roadmaps.

I am hopeful that these documents will not only promote technological advancements but also cultivate vibrant R&D eco-system for electric mobility in the country.

(Dr. Anita Gupta)

Room No.8, S&T Block-I, Technology Bhavan, New Mehrauli Road, New Delhi-110016
Tele.: 011-26523977, 26590213 Website: www.dst.gov.in / www.nstedb.com
E-mail : anigupta@nic.in / anitagupta2004@gmail.com

भारतीय प्रौद्योगिकी संस्थान मुंबई
पवई, मुंबई - 400 076, भारत

Indian Institute of Technology Bombay
Powai, Mumbai - 400 076, India

दूरभाष/Phone : (+91-22) 2572 2545
फैक्स/Fax : (+91-22) 2572 3480
वेबसाईट/Website : www.iitb.ac.in

IIT Bombay

MESSAGE

Electric Vehicles are sustainable alternatives to Internal Combustion Engines (ICEs) as they produce zero local emissions and reduce dependence on imports of fossil fuels thereby ensuring energy security. Spurred by favourable schemes and policies by the Government of India, Indian Electric Vehicle sector has shown remarkable growth over the last few years.

With growth, there are still many challenges that need to be addressed for effective adoption of EVs in the country. These include the high cost of vehicles, limited range, concern about vehicle safety and lack of adequate charging infrastructure. In addition, innovation, design and development to increase efficiency and performance of the EVs and testing competency are also need attention. In this context, Department of Science and Technology (DST) in consultation with various stakeholders brought out a consolidated White Paper on *EV Evolution: Catalysing Technology led Ecosystem for e-Mobility,* which was released in the month of February, 2024. This document highlighted both hindrances being faced and also provided technology solutions to address these issues to strengthen Indian EV industry through R&D intervention.

DST is now bringing out three R&D roadmap documents on EV battery, EV motors and power electronics, and EV charging infrastructure, which have been prepared after extensive consultations with the stakeholders over a period of two years. These documents are crucial for setting up R&D targets and work towards developing indigenous products/systems that conform to international standards to help industry to meet domestic market and as well increase export potential in this domain.

I extend my sincere gratitude to Dr. Abhay Karandikar, Secretary, DST for giving me the opportunity to Chair the Advisory Committee. I also thank Dr. Anita Gupta, Head, Climate, Energy and Sustainable Technology (CEST), DST for her support in this endeavour. Special thanks to members of the Advisory Committee, especially Prof. Siddhartha Mukhopadhyay, for their valuable contributions in shaping these documents.

I hope that these documents are of use for planning and implementation of R&D programmes in promoting research and advancing domestic manufacturing competencies in achieving the targets of Atma Nirbhar Bharat (Self-Reliance).

Prof. B.G. Fernandes
Chairman, Advisory Committee
White Papers on e-Mobility, DST

MINISTRY OF SCIENCE & TECHNOLOGY

प्रो. प्रदीप श्रीवास्तव, पीएचडी, एफआईई
कार्यकारी निदेशक
Prof. Pradeep Srivastava, PhD, FIE
Executive Director

प्रौद्योगिकी सूचना, पूर्वानुमान एवं मूल्यांकन परिषद् (टाइफैक)
(विज्ञान एवं प्रौद्योगिकी विभाग, भारत सरकार की स्वायत्तशासी संस्था)
5वी मंजिल, ए आई ब्लॉक, प्रौद्योगिकी भवन, न्यू महरौली रोड़, नई दिल्ली-110016 (भारत)
TECHNOLOGY INFORMATION, FORECASTING & ASSESSMENT COUNCIL (TIFAC)
(An autonomous body of Department of Science & Technology, Govt of India)
5TH FLOOR, AI BLOCK, TECHNOLOGY BHAWAN, NEW MEHRAULI ROAD, NEW DELHI-110016 (INDIA)

Message

India's journey towards a Viksit Bharat has to meet three major imperatives of sustainability – reducing greenhouse gas (GHG) emissions, ensuring energy security and improving ambient air quality. The Intergovernmental Panel on Climate Change has estimated that to limit the global warming within 1.5°C limit, emission reduction of 43% must be achieved by 2030 as compared to 2019 level. Reducing carbon emission along with carbon-capture and sequestration (CCS) has become extremely unavoidable measure. Conventional transport modes, as distributed source of emissions, pose enormous challenges in this regard. Electric mobility not only reduces GHG emissions, but also enables utilization of renewable energy sources for the transport sector, contributing to energy security too.

The Hon'ble Prime Minister of India, at the 26th session of the United Nations Framework Convention on Climate Change (COP 26), announced India's target to achieve Net Zero emissions by 2070. He also specified the Panchamrit action plans. While moving towards this direction, India aims to achieve CO_2 emission reduction of 1 billion tons by 2030. Electric mobility is one of the key technologies that may help India towards meeting these targets. Actions towards promoting electric mobility need to focus on overcoming the hindrances, which at a broader level, may include considerations of cost, convenience, performance, infrastructure readiness, supply-chain sustainability and even environmental issues. It is an appropriate time to identify the roadmap for overcoming such hindrances. Department of Science and Technology has aptly taken a lead in this direction.

One of the broader themes under this initiative is focused on Power Electronics, Machines and Drives (PEMD), which play an important role in efficient and effective operation of electric vehicles. Power-electronic systems control the flow of electrical energy along the vehicle drivetrain, and ensures optimum operation of the electric motor. Power electronics also plays a crucial role in efficiently interfacing the electric vehicle with the supply of electricity.

TIFAC is extremely happy to have led the preparation of the roadmap on PEMD under this initiative by the DST. Since almost last fifteen years TIFAC has been at the forefront of catalysing electric mobility R&D in the country, and would like to continue such efforts to support the Government agencies and other stakeholders in this regard. I have a strong understanding that this roadmap will be an effective reference towards formulating appropriated national level initiatives and inspire researchers, industry and other stakeholders in their efforts to place India as a global leader in electric mobility.

(Pradeep Srivastava)

Website : www.tifac.org.in आप हमसे हिन्दी में भी पत्र व्यवहार कर सकते हैं। **www.pfc.org.in**
Telephone : +91-11-2651 1227, 2651 1245 • E-mail : ed@tifac.org.in, drpradeep19@gmail.com

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विज्ञान एवं प्रौद्योगिकी विभाग
भारत सरकार
Department of Science & Technology
Government of India

Suresh Babu Muttana
Scientist E
Coordinator, EV R&D Roadmaps

GENESIS AND KEY CONTRIBUTORS

NITI Aayog entrusted DST to work on technologies to overcome hindrances in e-Mobility. Over the last two years, DST conducted a series of interactions with stakeholders viz. vehicle OEMs, battery manufacturers, electrical & electronics industry, R&D labs, academia and think tanks to identify key challenges and potential R&D solutions to address these issues. These deliberations led to preparation of a White Paper on Catalysing Technology led Ecosystem for e-Mobility, which was released on 28.02.2024 by Dr. Jitendra Singh, Hon'ble Minister of State (I/C) for Science & Technology, GoI.

As an extension to the above effort, DST has now come up with detailed R&D Roadmaps in key thrust areas of electric mobility viz. (a) Tropical EV battery, (b) Power electronics, Machines and Drives; and (c) EV charging infrastructure. These reports have gone through several iterations and inputs received from major auto industries and other stakeholders from the entire EV ecosystem have been incorporated.

I would like to express sincere gratitude to Prof. Abhay Karandikar, Secretary, Department of Science & Technology (DST), GoI for his kind support and overall guidance. I would like to thank Dr. Anita Gupta, Head, CEST Division, DST for her concerted efforts and guidance in shaping the recommendations as well as program plans aligned with national goals.

I also extend deeper appreciation to the Advisory Committee led by Prof. B.G. Fernandes, IIT Bombay, and the noteworthy contributions by domain experts namely: Dr. K Raghunathan, IIT Madras; Prof. Siddartha Mukhopadhyay, IIT Kharagpur; Mr. Sajid Mubashir (former), DST; Dr. Z.V. Lakaparampil (former), CDAC ; Mr. Suuhas Tendulkar, ERF Global; Ms. Veena Koodli, Robert Bosch; Mr. N. Mohan, CESL; Mr. Kiran Deshmukh, Sona Comstar, who have extensively contributed in preparation of these R&D Roadmaps with quality content and in-depth analysis and actionable framework.

I would like to express sincere thanks to the lead authors: Ms. Moushumi Mohanty, Ms. Mrinal Tripathi, Mr. Rohit Garg, Ms. Anannya Das, Centre for Science and Environment (CSE); Dr. Raghunathan, IIT Madras; Mr. Sajid Mubashir (retired), DST; Mr. Arghya Sardar, TIFAC; Dr. Parveen Kumar, WRI India; Mr. Suuhas Tendulkar, ERF Global; Ms. Veena Koodli- Robert Bosch; and Mr. N Mohan, CESL, who have put together initial drafts and also immensely contributed in finalisation of these documents. I would like to acknowledge especially Dr. Reji Mathai, Director, ARAI for reviewing R&D Roadmap on EV Charging Infrastructure.

(Suresh Babu Muttana)

Technology Bhavan, New Mehrauli Road, New Delhi -110016; Email: sureshbabu.muttana@gov.in
+91-11-26590593; www.dst.gov.in

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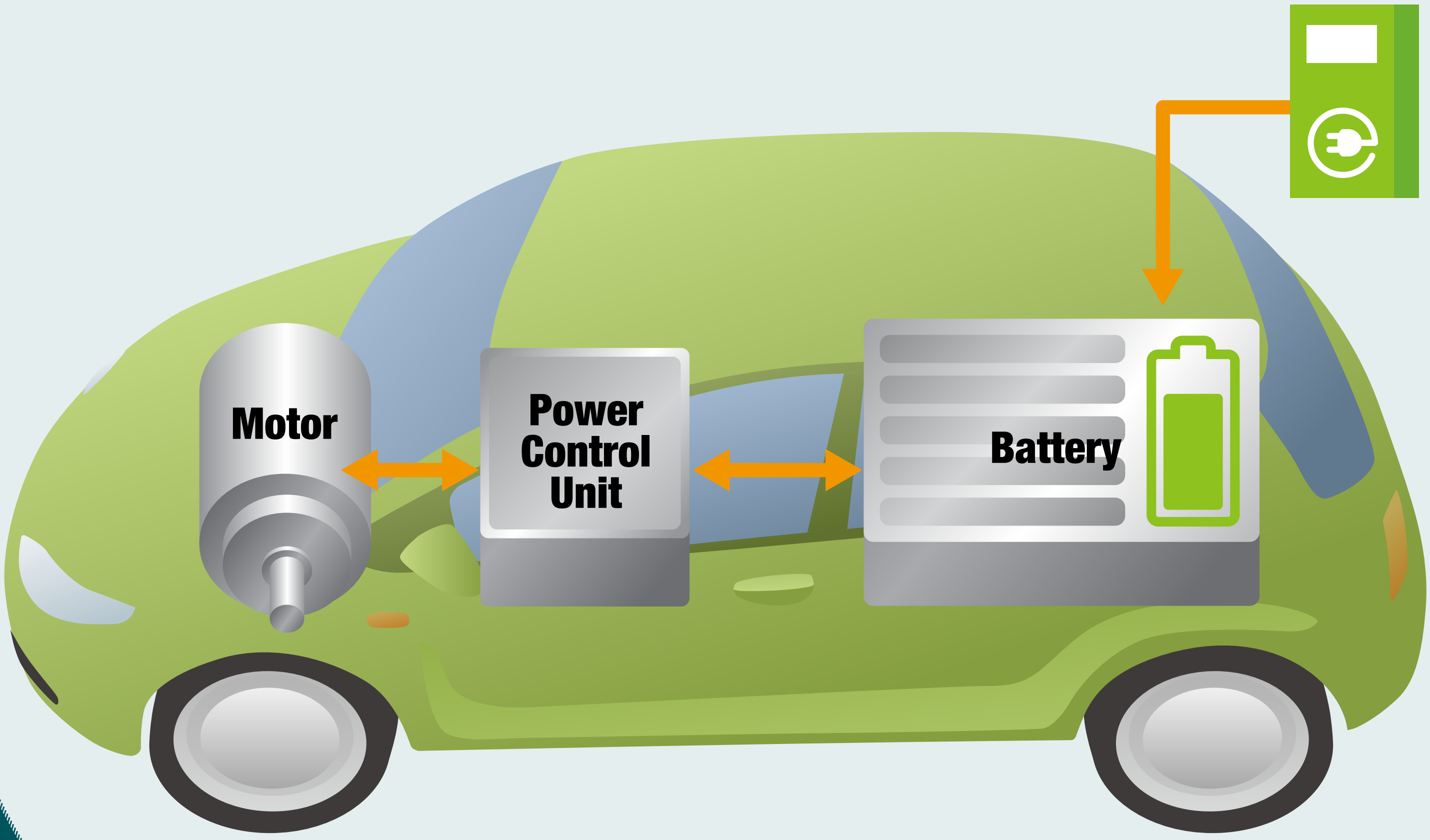

EXECUTIVE SUMMARY

Some of the major hindrances to widespread use of Electric Vehicles (EV) in the country are: high initial cost, limited range, safety risks, , high charging time, heavy weight, battery degradation as well as the inadequate indigenous competencies for development and manufacturing of high quality EV components and subsystems. Power Electronics, Machines, and Drives (PEMD) technologies have a key role in overcoming many of these hindrances.

Electric Vehicle power electronics is evolving to a stage wherein conventional silicon-based power semiconductor devices are reaching their limits, and therefore, Wide Band Gap (WBG) semiconductors are expected to gain more importance. A necessary step to leverage this is the design of the passive components, converter topologies, and thermal management system. Packaging of WBG semiconductor devices needs attention. The development of various topologies for inverters and DC-DC converters with higher power density, high-temperature operation, and high switching frequency has been a major focus of power electronics for electric vehicles in recent times. India is importing key components like power modules and their controls. The ability to design and manufacture them will significantly boost the industry's competitiveness. Currently, India does not manufacture or package semiconductors, although some of the major global players have established their R&D/Design Centres in India. Design and fabrication of WBG semiconductors is therefore an essential step for the modern EV power electronics ecosystem. Overall, India needs to develop competency in the design and fabrication of power semiconductor devices and circuits.

Developing appropriate control systems for the effective functioning of the power electronics systems of EVs is another critical issue, particularly in the context of WBG devices-enabled power electronics. Development of energy aware drives and integrating them with high level vehicle supervisory control features such as ESC, ADAS, ABS etc. need to be developed. On-line condition monitoring and prognostics of the PEMD subsystem and fault tolerant electric motor drives are largely absent in current day products. These can compensate partly for indigenous and cost effective manufacturing and boost overall product quality, maintainability and reliability.

Various commercially available and emerging motor technologies are used in electric vehicle traction. Induction motor (IM) with thin lamination and liquid cooling is popular in heavy duty vehicle applications. To meet the demand for compact, high-speed motors with high torque and power density, Permanent Magnet Brushless DC (PMBLDC) and Permanent Magnet Synchronous motors (PMSM) are widely used in vehicles and will remain the preferred choices, at least in the short term. Therefore, developing the indigenous manufacturing and supply chain processes for IM/PMBLDC/ PMSM motors for EVs are critical. Developing low-cost, non-rare earth motor technologies is essential for the long-term sustainability of the Indian electric vehicle ecosystem, and options such as the Switched Reluctance Motor (SRM) and the PM assisted SynRM have emerged as alternatives to the PMSM. Using magnets that do not use critical raw materials or a reduced amount of these is another approach to addressing the issue of sustainable indigenous supply of EV motors. Improvements in the reliable induction motor technology for high efficiency and variable speed EV applications need to be explored. Improved thermal management appropriate for Indian conditions of motors need to be taken up for better efficiency and useful life. Overall, innovations in motor architecture/ topology such as hybrid excited synchronous motors, axial flux motors etc. and their related aspects of quality, cost and reliability need to be focussed on.

Development of tools and methods for integrated multi-physics design of motors with multi-objective optimization for various categories of electric vehicles will be important to enable Indian EV motor manufacturers to deliver solutions for vehicle OEMs.

Special emphasis should be placed on developing competency in the various aspects of the electric motor supply chain, including process and equipment for design, manufacturing, packaging, integration and assembly of motor components including magnets, stampings, rotors, windings, sensors etc. Precision manufacturing capabilities are vital in developing high-speed, high power density and efficient electric motors. Additive manufacturing can potentially help develop lightweight electric motors and their integration with the drive units.

Catalysing technology development and adoption in the field of PEMD is envisaged to be achieved through an industry-led R&D ecosystem comprising a few Innovation Clusters or Centres of Excellence. The Government may initially provide financial support for preparing the Detailed Project Report for the Innovation Clusters.

Three functional Centers of Excellence (CoE) may be considered: 1) CoE for Electric Vehicle Motors, 2) CoE for Power Electronic Converters, and 3) CoE for the Integration of Electric Vehicle Drive Systems.

National consortia must be initiated to network academia, industry, and R&D with CoEs. These consortia can play important roles in the specification of EV propulsions, the standardization of motors, controllers and drives, and the strategy to build technological competence and to ensure the availability of skilled manpower.

It is envisaged that relevant Government initiatives, such as the India Semiconductor Mission and the National Mission on Power Electronics Technology (NaMPET), will be closely linked with those undertaken for Electric Mobility.

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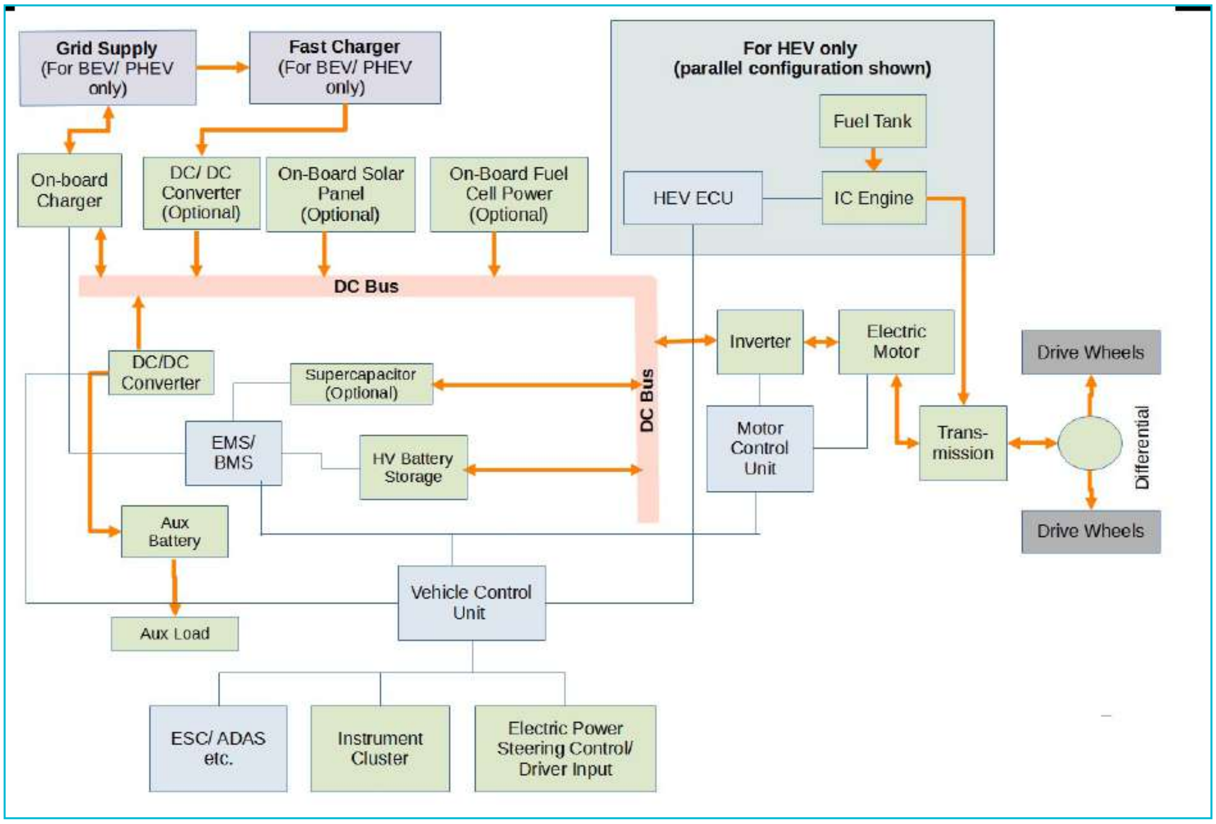
THE EV SYSTEM: OVERVIEW AND TECHNOLOGY STATUS

1.1 The Electric Vehicle Drivetrain: Power and Energy Management

An electric vehicle (EV) integrates various electrical, electronic, electrochemical, mechanical and thermal systems, as shown in Figure 1.1. The performance of the electric vehicle depends on the integrated performance of the battery, motor, and control subsystems. In case of hybrid electric vehicles, the integration needs to include the IC engine subsystems, such as gears, Energy Management System (EMS) etc. Power electronic circuits enable the flow of electric power from the battery pack to the motor and to auxiliary systems. The motor speed and torque are controlled by appropriate control of circuit topology. Motor control also involves efficient regenerative braking, which can help improve overall energy efficiency.

Figure 1.1: Indicative Generic Block Diagram of Electric Drive Vehicles



Modern electric vehicles have a central control system called the Vehicle Control Unit (VCU) which incorporates the EMS. The VCU decides set points for torque and speed ensuring the optimal energy utilisation from the battery pack to different loads based on vehicle level demands. These are determined based on the status of power sources, and the level of power consumption envisaged for the intended trip and the driver's behaviour. The EMS communicates closely with the Battery Management System (BMS), the ADAS, the ABS, ESC etc. It also communicates with Motor Control Units (MCU) and DC-DC converters to control the power flow among powertrain components optimally to achieve the desired motion of the vehicle for a safe, speedy, comfortable and energy efficient drive.

The battery is the primary source of energy and power in pure EVs often called Battery EVs (BEVs). It is possible to supplement a small percentage of energy with rooftop solar panels. The battery may have a voltage ranging from, say, 48V to 800V, and energy storage capacity in the range of, say, 2kWh to 100kWh or more depending on the vehicle energy requirement. The same battery can supply power to different voltage and power sub-systems, with the help of Power Electronic converters.

In parallel Hybrid Electric Vehicles (HEVs) there is an engine burning fuel such as, Diesel, Petrol or CNG in addition to the motor supplying tractive power and typically, the battery size in these vehicles are relatively much smaller. For a special category of parallel HEVs called Plug-in Hybrid Electric Vehicles (PHEVs), the battery can be charged from the electric grids. In series HEVs the engine is not mechanically coupled to the motor, but only used to drive a generator to charge a battery, which drives a motor that drives the vehicle. Here the battery size may be higher than parallel HEVs but smaller than BEVs. Power-split HEVs incorporate a mixed series-parallel architecture. There are also various other categories of hybrids, such as Fuel Cell HEVs which use Hydrogen to charge up batteries. Among Indian OEMs, typically, there is a lack of focus on strong hybrids, although many ICE vehicles are being converted to mild hybrids. In the medium term, till the price and technology improve for energy sources like Hydrogen and energy storage like batteries, HEVs can potentially improve adoption and reduce emission. While the motor and power electronic technologies are identical for HEVs with those for BEVs, there are significant differences in drive and vehicle control, particularly in energy management. These can be built up rapidly with state initiatives and support.

Both BEVs and PHEVs need chargers for charging the battery. Chargers can be on-board or they can be off-board and part of the charging infrastructure of EVs distributed across locations. Chargers are also realized using PE circuits. Chargers are covered in a different volume of the report.

In EV systems, a variety of power electronic converters are needed. On the load side,

- The inverter drives the traction motor. The voltage and power ratings are high and they depend on the vehicle size and application.
- While the traction motor operates at higher voltages, auxiliary loads like fans, air conditioning, wiper blades, etc., normally operate at 48V DC. The lighting system and control circuits operate at 12V DC. DC-DC converters are required to transfer the power from main batteries to auxiliary loads.
- Ultra-capacitors facilitate quick storage of energy during regenerative braking or fast and quick charging along with the battery. This also needs a power electronic converter. At present these are rarely used in commercial vehicles but may become more common if the price of these capacitors are reduced.
- If solar panels are used on the vehicle's rooftop and fuel cell systems are used to supplement power along with the battery, then power converters, which are multiport converters, are needed to charge the battery from these devices.
- For HEVs the battery is charged by the engine either by a dedicated generator in series hybrids or by using the traction motor in the generator mode in the parallel hybrids. This requires power electronic converters too.

Power distribution needs to be dynamic and responsive to changing driving conditions and driver inputs. Situations such as high-speed driving or rapid acceleration require higher energy allocation to the traction motor. But at lower speeds or during idle times, there may be a higher energy allocation for auxiliary systems like HVAC.

The Battery Management System (BMS) is a critical component of electric vehicles' overall energy management scheme. It handles the electrical, thermal, and safety management of the battery packs.

This report focuses on BEVs since these solely constitute the 2-wheelers and 3-wheelers. Among 4 wheelers also BEVs constitute the majority although strong parallel HEVs have started to appear in the market and are well received.

1.2 Power Electronic System Components

1.2.1 Motor Controller Unit (MCU)

The MCU manages the operation of the electric motor, including starting, braking, stopping, and changing the speed and torque of the motor. It receives signals from the VCU and controls the power output of the inverter to control the motor. Constraints on component size and weight demand high frequency inverters which require high speed computation. Typical modern MCU hardware integrates FPGA subsystems with microcontrollers/DSPs for cost/performance optimizations. Since the MCU needs to operate with BMS and VCU, the communication interface and its overall coordination can affect system performance. Quality and reliability of the motor control performance over the lifecycle of the motor and the inverter is of prime importance. This implies development of advanced control for performance robustness against manufacturing tolerances and degradations, as well as tolerance to faults in power devices, sensors, magnets, bearings, shafts etc. For high reliability of the high frequency and high power density inverters WBG devices are preferred, requiring high resolution synchronization of switches and predictive thermal management by the MCU. Finally, packaging with circuit board, power supply and heat-sink integration, EMI/EMC etc. need to be achieved. Embedded software aspects such as high level tool interfaces, upgrade features, diagnostics etc. are also to be addressed.

1.2.2 Inverter/ Converters

At the heart of the systems providing power to various components of electric vehicles are power semiconductor switches that control the flow of electrical power by turning on and off at appropriate times. These include IGBTs, MOSFETs and now the switches made of wide band gap devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN). The circuit types are:

1. ***DC/DC converter***: The DC/DC converter is used to step down the high-voltage DC power from the battery to a lower voltage that can be used to feed the power auxiliary systems such as lights, air conditioning, audio systems and various electronic control functions, such as the Vehicle Control Unit (VCU). The converter may also provide a regulated DC voltage to charge the 12-volt battery that powers the vehicle's starter motor and other auxiliary systems. In some cases, DC/DC converters are used to step up the voltage to make the motor operate at a higher voltage for better efficiency. Generally, these converters are bi-directional to support regenerative braking.

2. ***AC/DC Converter***: The AC/DC converter acts as the interface between the on-board battery storage and the grid. Conventionally, two-level voltage source converters are used for this purpose, which has certain disadvantages such as limited power rating and high harmonic distortions. Adding passive, active or hybrid filters to address this issue increases size and cost of the system. An electrolytic capacitor is also required to support the intermediate dc-link and reduce voltage ripple. Use of multi-level converters can be effective in reducing harmonics. Electric Vehicle chargers, both on-board and off-board, may have two stages (AC/DC followed by DC/DC) or a single stage (combined AC/DC and DC/DC). The two-stage topology achieves high power factor, wide line regulation performance and sinusoidal charge current. But it is associated with higher cost. On the other hand, the one-stage topology is compact, low cost and involves simpler control. However, galvanic isolation is essential for safety, and the issue of large low-frequency ripple needs to be dealt with appropriate control.

3. ***Inverter***: The inverter converts DC power from the battery into variable frequency AC power that drives the electric motor. By adjusting the frequency and voltage of the AC power, the inverter controls the rotational speed of the traction motor and provides

the required torque to drive the motor at that speed. The inverter also provides the path for power flow during the regenerative braking. The inverter drive architecture can vary with the type of motor used. Digital or mixed analog digital control schemes are available. Turn-on and turn-off losses at the switch determine efficiency of the converter. Minimizing losses is important both for improving electric range and also to reduce thermal stresses on the switches. Various switching schemes control the voltage, current and thermal stresses on switches. Relative spacing of the switching instants of the currents on various windings with respect to the rotor axial and angular position determines the torque waveforms and control average and ripple values of torques and also minimize cogging and mechanical stresses on parts of the motor. Careful considerations of these are critical for energy efficiency, quick response and reliability of the drives.

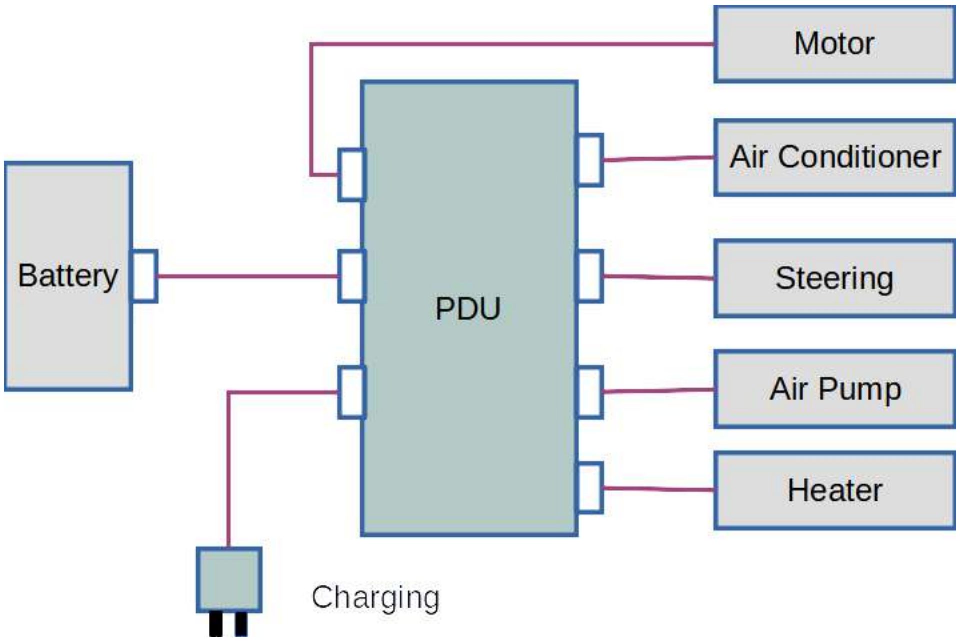
1.2.3 Battery Management System (BMS)

The BMS manages the charging and discharging of the battery to keep it within safe operating conditions and ensure its durability. It also monitors the state of charge (SoC) and state of health (SoH) of the battery. These are important estimates that need to be continuously updated and used for vehicle supervisory control to optimize energy efficiency, drive experience, safety and useful life. The operation of the BMS and the MCU need to be coordinated to maintain the drive performance over the battery life and charging cycles and to restrict unsafe operations that may damage the battery or cause safety events. The BMS also takes care of cell level monitoring and charge control of the battery pack. It facilitates battery life and capacity utilisation by balancing the charge of the cells which may age differentially with respect to time due to manufacturing variations or temperature gradients existing in the battery pack. Most of the commercially available BMSs use passive cell balancing which is slow and results in energy loss due to dissipation in the resistors. Active cell equalization techniques can potentially reduce such energy losses using power electronic balancing circuits and also enhance battery life and facilitate maintenance. Since the battery characteristics change with variation in SoC and SoH, coordinated control of the battery and the drive through BMS-MCU interaction is essential to guarantee nominal performance of EVs over the lifecycle. Similarly, the BMS also needs to interact with the charger for safe and efficient charging. The interaction of the BMS with the MCU, charger, balancer etc. may be direct or through the VCU, as found typically in larger vehicles.

1.2.4 Power Distribution Unit (PDU)

The PDU distributes the electrical power from the battery to the various subsystems of the vehicle, including the electric motor, charging system, and auxiliary systems. The system supports functions such as charge and discharge control, high-voltage component power-on control, circuit overload and short-circuit protection, current leaking protection, ingress protection (IP), high-voltage sampling, and low-voltage control. These functions protect and monitor the operation of the high-voltage system.

Figure 1.2: Power Distribution Unit



The PDU comprises high-voltage DC connectors, fuses (ceramic-based and pyro-fuse), pre-charge circuitry, isolation monitoring to monitor isolation between the high-voltage bus and chassis, a high-voltage interlock loop (HVIL) to ensure the integrity of the high-voltage connectors, etc. The high-voltage components are electrically connected through the busbar and wiring harness to create the high-voltage system for EVs. Modular and configurable power distribution units combine fuses, relays, microcontrollers and multiple layers of interconnections into a single integrated assembly.

1.2.5 Thermal Management System

The thermal management system regulates the temperature of the power electronics and battery pack to prevent overheating and prolong the lifespan of the component battery cells and switches. Air and liquid cooled systems are both prevalent. Air cooled systems are common for two and three wheelers, while for four wheelers liquid cooling are typically used. Thermal management is a critical technology that helps improve the reliability and safety of EVs. It is important to minimise the energy consumption of thermal management. It is also important to ensure that heat transfer coefficients do not degrade over time and non-uniform heat transfer leading to development of hot spots or zones do not happen. Predictive thermal management strategies can also be incorporated into the VCU using temperature sensor feedback. Safety related development of standards and best practices for manufacturing and operation are important.

1.3 Drive System

The EV Drive system comprises the battery, the inverter, the motor and the transmission to the wheels. There are various architectures for efficient operation of the above subsystems. Almost all commercially available electric 4-wheeled vehicles use the traditional central drive architecture of conventional ICE vehicles. Wheel hub drive has been used in electric scooters. Elimination of the differential and driving shaft is an advantage of this configuration. In a slight variation of such a system, the electric motors can also be connected to the wheels through a reduction gear.

The concept of four independent in-wheel-motor drive have also been explored. The major advantages of such systems are drastic reduction in the mechanical linkages resulting in reduction of losses. Such a system enables all wheel independent steering. Torque control of each wheel can be independent and more precise. Implementing advanced control functions like Antilock Braking System (ABS), Anti Slip Regulation (ASR), Electronic Stability Program (ESP) etc. become more feasible. However, the technical challenges that need to be overcome include the increased unsprung mass. The design of an in-wheel motor needs to consider the limited packaging space, harsh environment and safety and reliability requirements.

There is a global interest in creating higher levels of autonomy of vehicles. These vehicles interface the vehicle drive to vehicle sensors such radars, lidars or cameras as well as cloud and GPS interfaces. They also employ advanced supervisory control for energy management, safety, fault tolerance and drive comfort. Drives also need to be adaptive to feedbacks from diagnostics and prognostic systems for cost/performance optimization over vehicle lifecycles. Today, such systems are delivered mostly by global tier-1 suppliers for 4-wheeler vehicles. For 2W and 3W vehicles, these systems are typically rudimentary, if not absent. Thus, research and innovation on EV drives is an important priority.

1.4 Simulation Environment for Electric Vehicle Design

The design of EVs requires accurate multiphysics models for the energy storage, driveline, mechanical, and control systems. The vehicle power system and driveline assemblies should be evaluated by simulation with control strategies. This requires offline, Software-in-Loop, real-time and Hardware-in-Loop (HIL) simulation.

In EV simulation for design, the following functions need to be supported.

- Performance evaluation (acceleration, gradeability, maximum cruising speed, and road cycle requirements)
- Tuning of embedded real-time controllers specific to EVs with transmission
- Multi-physics simulation of EV subsystems for evaluation of power and energy flow, thermal characteristics
- Sizing of battery systems, battery pack thermal and electrical design

1.5 Prospective Role of PEMD to Overcome Hindrances to Electric Mobility

Power electronics, machines, and drives can play several important functions in addressing the hindrances to electric mobility. These are listed in Table 1.1.

Table 1.1: Prospective Role of PEMD

Hindrances	Role of Power Electronics, Machines and Drives
High initial cost of vehicles	» Indigenisation of power electronics systems, components, devices etc. Presently, most of these are imported » Optimising the architecture and specifications of power conversion units leading to higher efficiency, reduced size and ratings, and reduced number of components » Optimising costs of magnets, cooling system, packaging, stampings, coils
Limited range	» Enhance regenerative braking, efficiency of the drivetrain, faster charging » Reduce weight by using higher power density components, packaging » Simpler thermal management system
Safety	» Control of the charging depending on SoH/SoC » Better thermal management system » Diagnostics and prognostics of the traction motor and the battery pack. » Advanced Gate Drive to protect IGBT / MOSFETs
Higher weight	» Enhance power density of motor and other components that handle flow of power
High charging time	» Fast charging or battery swapping » Standardisation/ interoperability of charging systems » HV and DC fast charging for large vehicles » Develop High Voltage System to accelerate charging time
Infrastructure and Competency for development and testing	» Setting up of CoE for R&D, support to MSME and skill building

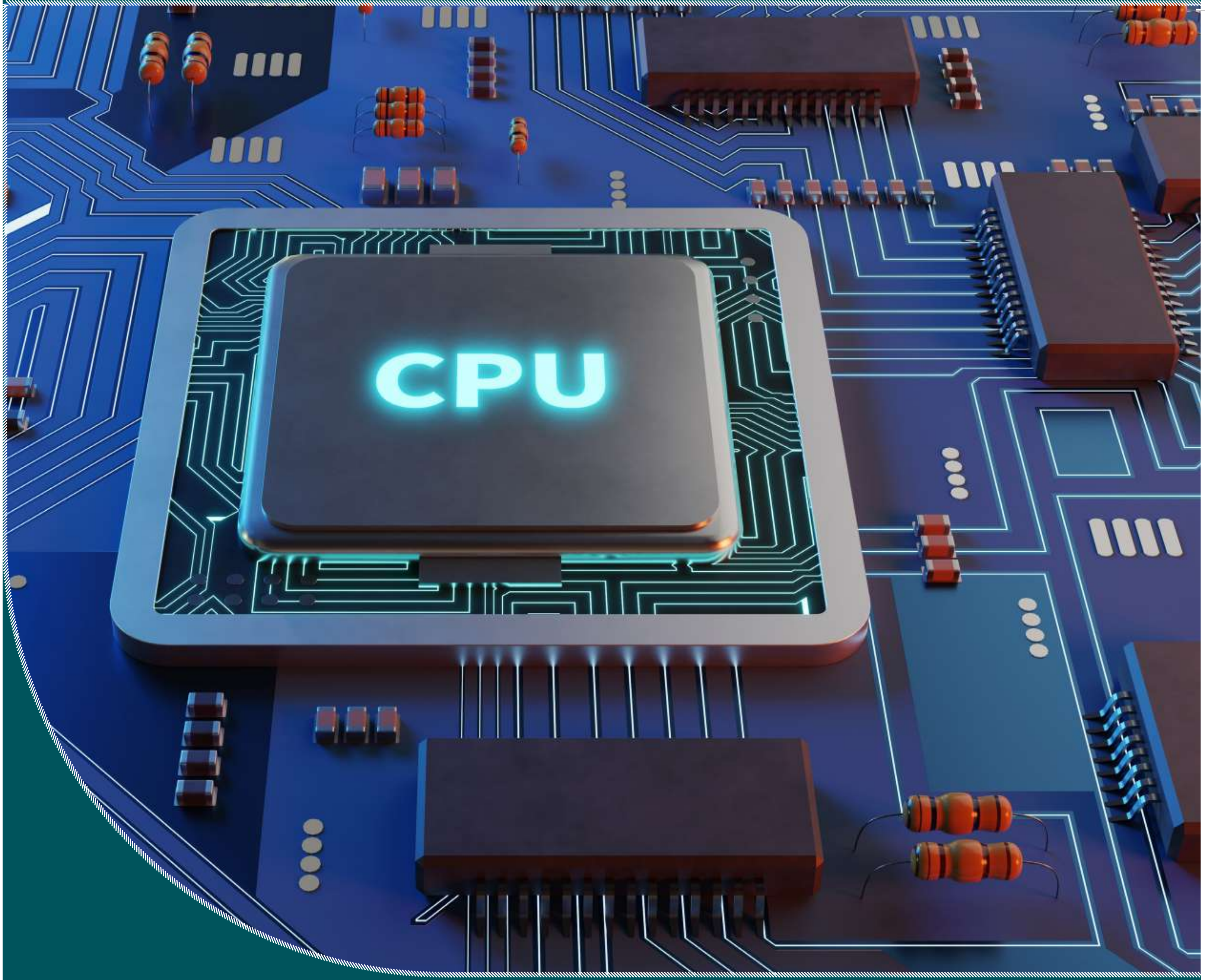
1.6 Manufacturing Competency in India in PEMD

India is importing key components like the power modules and controls. The ability to design and manufacture them will significantly boost the industry's competitiveness. India has no manufacturing or packaging of semiconductors, although some of the major global players have established their R&D/ Design Centres in India. An overview of present status of PEMD value chain in India is presented in Table 1.2.

Table 1.2: Status of the PEMD Value Chain in India

		Status
Semiconductor Manufacturing	Wafer Manufacturing	No Manufacturing/packaging (100% import dependency)
	Die Manufacturing	No Manufacturing/packaging (100% import dependency)
	Device Processing	There are a few new entrants to the packaging and device processing
PCB Assembly	Passive Components	Manufacturing of resistors and capacitors. Competency development in magnetics required
	PCB	Limited competency
	Sensors	Limited competency
Module	Power Module Manufacturing	Partially imported, although India has a hold in power modules manufacturing
Converter/ Inverter	DC-DC Converter	Local manufacturing of power converters for residential/ commercial scale back up and solar PV systems
	Inverter	Local manufacturing of power converters for residential/ commercial scale back up and solar PV systems
Traction Motor	Motor Controller	Several domestic manufacturers offer motor controllers
	Materials for motor	Established domestic manufacturing on iron and steel. However, no manufacturing of electrical steel as well as magnets required for PMSM/ BLDC
	Motor electrical systems	Circuit boards, diodes, relays Case display, spare parts
	Motor manufacturing equipment	Machines are manufactured in the country. However, competency in high precision manufacturing systems required
	Traction Motor	Manufacturing of BLDC/PMSM has been taken up by few companies recently. Technology development for SRM is also pursued by some companies. Advanced technologies for hairpin winding are required.

In this chapter an overview of the major PEMD subsystems have been presented, followed by some of the main R&D aspects which are important for removing the hindrances to EV adoption. A broad overview of the status of manufacturing competency is also presented. In subsequent chapters a more detailed look at the technological priorities is present.



02

TECHNOLOGY PRIORITIES IN POWER ELECTRONICS

2.1 Introduction

The delivery of electric energy stored in batteries to the motor, which converts it to mechanical energy, happens through the power electronic (PE) systems. Apart from this, power electronic converters are also needed for subsystems such as on-board charger, as well as the auxiliaries such as HVAC, lighting, power steering etc.

The desired characteristics of the PE systems are high power handling capacity, high frequency and low loss switching, low weight and compact size, high reliability over the life cycle at competitive cost. There are also desired characteristics of controlling the stability and bandwidth.

The PE systems typically comprise a power switch configuration such as an H-bridge, a control system electronic hardware for switching control, the sensor feedback interfacing and software for supervisory control of the overall system and finally the integration and packaging technology. Establishing the competency and an ecosystem for indigenous design and manufacturing of PE Systems and the development of a supply chain involve developments of tools and methods in each of these technology areas.

Typically, global Tier 1 suppliers have been providing solutions for OEMs. However, some Indian companies, have been building PE subsystems for automotive applications. On the other hand, there are also companies, which develop PE products and solutions for other energy and power applications like solar inverters, UPS, SMPS etc. They have inherent capacities to contribute to the automotive domain. However, it is essential to intensify the development of competency and resources in a much broader supply chain of PE systems, focus is required on various aspects of design and test, precision manufacturing and integration, reliability and durability of this critical subsystem to build cyberphysical, mechatronic EV system solutions.

This chapter focusses on specific aspects of PE systems for EV applications and R&D priorities.

2.2 Power Electronics Components

The design and manufacturing of power electronic systems and components for electric vehicle need to consider multi-disciplinary issues including electrical, thermal, mechanical, control, software, and magnetic aspects. Major components include inverter, DC-DC converters. These components comprise power switches, cooling system, capacitor, coils, sensors, control board, and housing etc. Power electronic converters are essential part of the electric vehicle charging systems too.

2.2.1 Inverter

A traction inverter supplies the variable frequency alternating current required for the operation of EV motors. The components required for the inverter include MCUs, SBCs, CAN and Ethernet Physical Layers (PHYs), and high-voltage gate drivers. Power conversion efficiency of the Traction Inverter directly influences the vehicle range (km/ charge). Typical efficiency of an inverter is of the order of 95% or more. In terms of power density, the US-DoE 2020 target of 13.4 kW/L for 30 kW continuous (55 kW peak) power traction inverter was surpassed by some manufacturers who achieved 15 kW/L [1]. Further, a revised target of 100 kW/L with 87% volume reduction was set for 2025 [2].

Various types of inverters are used in electric vehicles, with various characteristics and requirements in terms of voltage ratings, efficiency, frequency, cost, stability, current etc. depending on the application specifications. Some of these are:

- 3-phase main inverter for traction motor
- 3-phase inverter for control of electric motors of electric power steering (EPS), HVAC control, brake vacuum pumps, oil pumps, compressors etc.
- Isolated/Non-isolated DC-DC converter

Due to the need for high efficiency and low cost, EVs today utilize three-phase voltage source inverters (VSI) based on insulated gate bipolar transistors (IGBTs). Apart from this, alternative candidates for future inverters, i.e., current source inverters and multi-level inverters, including Neutral Point Clamped (NPC), Active NPC, flying capacitor, and the T-type NPC (TNPC), can be used with various switch and component technologies

2.2.2 Technology Targets

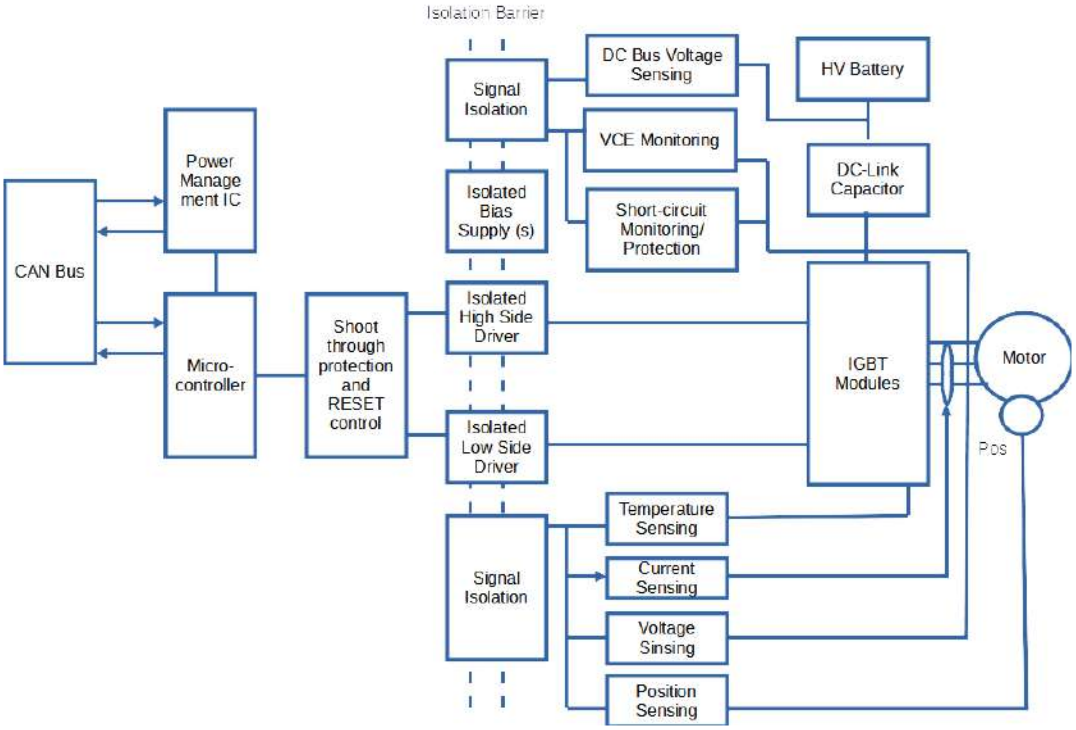
Design of an inverter needs to consider several aspects such as cost, weight, efficiency, failure tolerance, safety, reliability and manufacturability. Key performance parameters for inverters are high efficiency - for higher electric range, high-power density - for small size and low weight and high levels of functional safety to protect the vehicle operator and systems.

Higher frequency operation can potentially result in higher drivetrain efficiency; but the inherent switching losses of the device may outweigh this gain. Hence switching devices with low switching losses are desirable.

Typically, electric vehicles use IGBT or MOSFET based inverters. MOSFET has been the preferred choice for light vehicles such as two-wheelers. There are also technology options such as Gallium Nitride (GaN) technology implementation on DC-DC converters and traction inverters, SiC with advanced gate drivers or soft switching technology, and current source inverters with dual blocking devices.

The block diagram of a typical high-voltage traction inverter is shown in Figure 2.1. Several components of the inverter need to withstand high voltage and heavy current. They require high level of insulation and should be able to withstand such high voltage level.

Figure 2.1: Block Diagram of Traction Inverter



Galvanic isolation is required in the inverter for separating the control systems from the high-voltage domains. The inverter contains 6 switches, one for the high side and one for the low side for each phase. Isolated gate drivers are used in these switches.

Magnetics used in the inverter include inductors, transformers and line filters.

Electronic switching elements in an EV system are a source for Electromagnetic interference (EMI) which is an unwanted noise. EMI may cause electrical and electronic malfunctions, and can prevent the proper use of the radio frequency (RF) spectrum. Proper filtering, grounding, and shielding can limit the unwanted noise to an acceptable level. United Nation’s UNECE R10 is one of the most important automotive Electromagnetic compatibility (EMC) regulations, which covers more than 50 countries in the World and the 7 EMC Tests for Electric Vehicles is based on this regulation. They cover a wide range of requirements like Radiated Emissions, Radiated Immunity, Conducted Emissions, Harmonics Emissions, Flicker Emissions, Electrical Fast Transients (EFT) /Burst Immunity, Surge Immunity. The EMI reference standards for test frequencies, limits and levels change in time and are fixed by a standards committee under the direction of the national level test and certification agency.

The high voltage side on the inverter needs to be shielded to reduce the EMI of the traction system. EMI line filters, commonly using ferrite transformers, are applied to reduce electromagnetic interference (EMI) in electronic circuits. Ferrite transformers have the advantages of high permeability, ability to operate as high frequencies without generating EMI, and reduced losses. However, due to its low saturation flux density, the size of the device increases in case of high capacity power supplies.

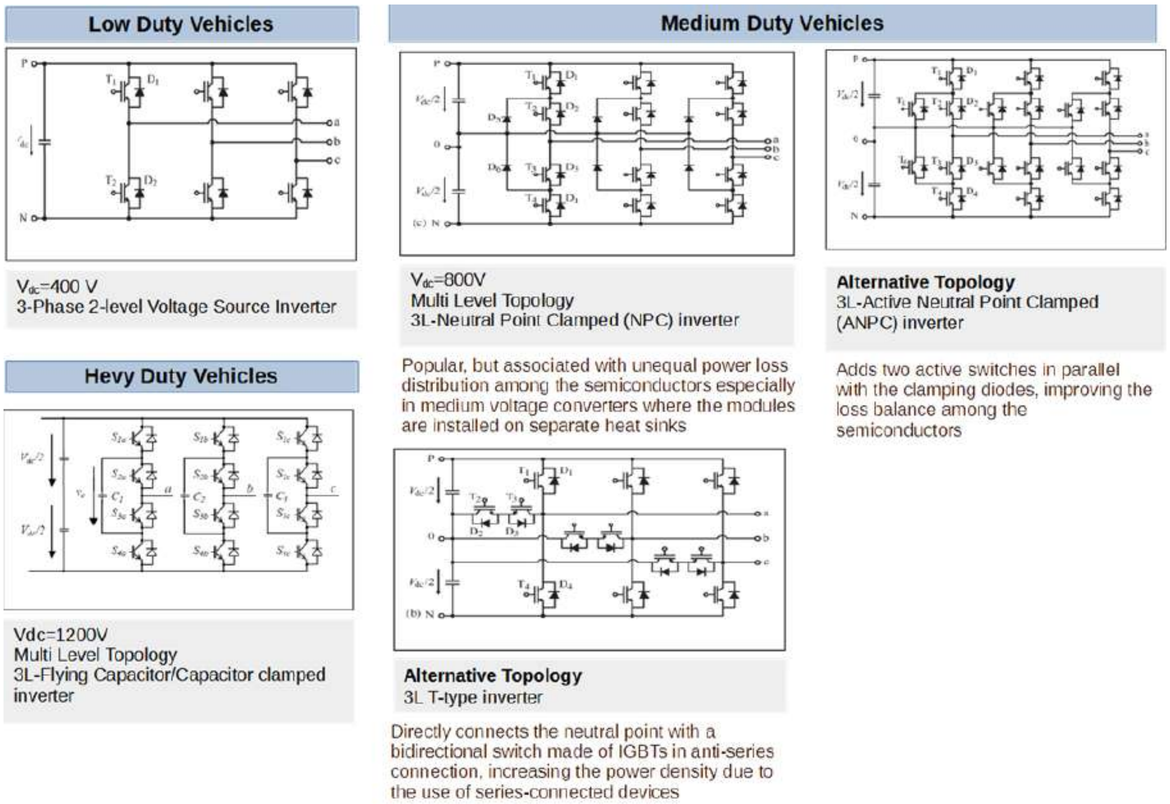
Power electronic switches in the inverter are the main source of harmonics and reduce its efficiency. Thus, minimization of Total Harmonic Distortion (THD) and discriminatory elimination of harmonics are desirable. It may be possible to reduce harmonics through structural modifications in the drive system or by using external filtering.

Inverters for passenger vehicles typically have switching frequencies in the range of 10-20 kHz. However, SiC inverter capable of switching current at up to 40 kHz has been developed [3] [4] and research activities even report switching frequency as high as 200 kHz [5]. The power-to-weight ratio of the contemporary IGBT inverter technology is up to 40 kW/kg [6]. Higher switching speeds causing high voltage gradients are more challenging concerning electromagnetic interference and isolation. Higher switching speed is also associated with switch failure.

2.2.3 Inverter Topologies

Inverter topologies suitable for various types of electric vehicles are shown in the Figure 2.2.

Figure 2.2: Inverter Topologies for Various Types of Electric Vehicles



Low Duty Vehicles

V_{dc}=400 V
3-Phase 2-level Voltage Source Inverter

Hevy Duty Vehicles

Vdc=1200V
Multi Level Topology
3L-Flying Capacitor/Capacitor clamped inverter

Medium Duty Vehicles

V_{dc}=800V
Multi Level Topology
3L-Neutral Point Clamped (NPC) inverter

Popular, but associated with unequal power loss distribution among the semiconductors especially in medium voltage converters where the modules are installed on separate heat sinks

Alternative Topology
3L T-type inverter

Directly connects the neutral point with a bidirectional switch made of IGBTs in anti-series connection, increasing the power density due to the use of series-connected devices

Alternative Topology
3L-Active Neutral Point Clamped (ANPC) inverter

Adds two active switches in parallel with the clamping diodes, improving the loss balance among the semiconductors

Among the inverter topologies, 2-Level Voltage Source Inverter (2L-VSC) is not attractive for medium voltage high switching frequency applications since the high switching losses caused by the maximum commutation voltage strongly limit the switch utilization and the maximum switching frequency. Three-level inverters (Neutral Point Clamped (NPC), Active

NPC, T-type NPC and Flying capacitor type) offer an increased efficiency at higher switching frequencies due to the low switching losses. There are additional positive impacts on the surrounding such as on the load machine losses or on the electromagnetic interference input filter volume. The 3L-NPC is widely used in medium voltage applications such as traction inverters. The main benefits are reduced switching losses and the ability to split the necessary blocking voltage into two series-connected devices. One of the most important drawbacks of the 3LNPC- VSC is the unequal power loss distribution among the semiconductors, which unbalances the junction temperature of these devices, especially in medium voltage converters where the modules are installed on separate heat sinks, limiting the maximum output power these can deliver.

Current Source Inverters (CSI) have not been used in automotive traction applications due to higher cost as compared to the VSI. They require capacitor filters on the AC output due to the high distortion of the line currents caused by the switching action. They are capable of boosting the input voltage and thus extending the constant power range of the electric motor without a separate DC/DC boost converter. There is a significant reduction in DC-link capacitor; however, DC-link inverter is still required.

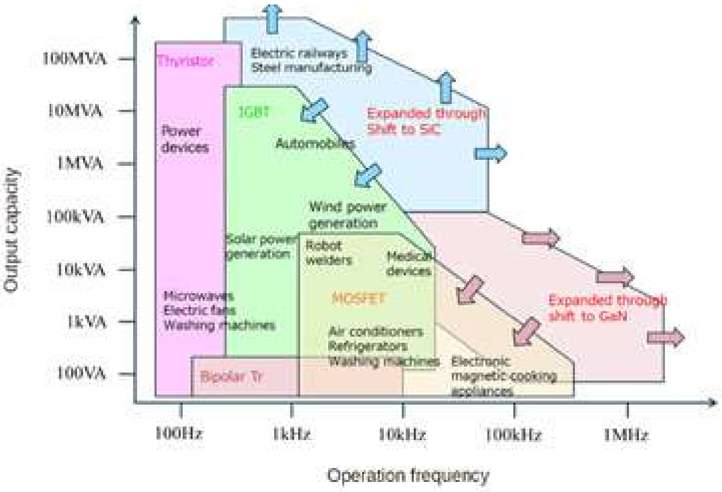
The Z Source Inverter (ZSI) combining characteristics of the VSI and CSI are promising alternative solution for EV applications as its buck-boost feature can handle, variation in the voltage of the battery pack.

Multilevel inverters enable higher VA rating and hence are particularly suitable for the heavy-duty trucks. The unique structure of multilevel voltage source inverters allows them to achieve high voltage and power levels without the use of transformers.

2.2.4 Challenges and Solutions

The targets can be achieved with the help of more power-dense solutions, faster-switching semiconductors, improved reliability, and materials with higher operating temperatures.

Figure 2.3: Power Semiconductor Devices and their application areas based on capacity and switching frequency



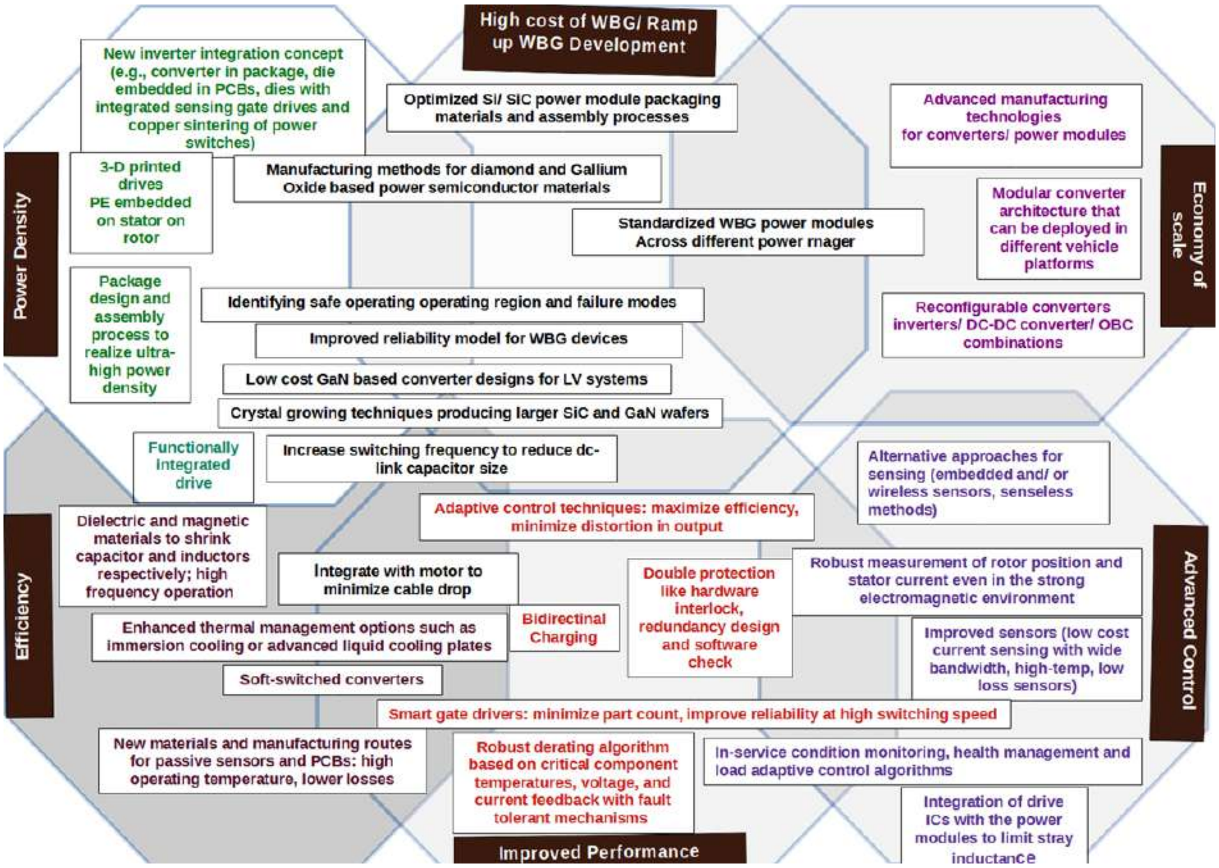
Source: Shin Dengen, [7]

One priority is the integration of the inverter subcomponents. This further requires advanced packaging that can provide electrical and thermal isolation and support significantly higher switching frequencies and power density. Such a high level of integration will need advanced thermal management systems and materials. Industry and research focus include component packaging, gate driver design, system integration, and manufacturing techniques. Replacing silicon (Si) power semiconductors with wide band-gap (WBG) devices like SiC and GaN also brings significant opportunities to overcome the challenges of designing the next generation of traction inverters.

Need for higher power density and efficiency has resulted into emergence of a trend towards integration of inverter, motor and gearbox into a single unit (e-Axle). This can potentially make mechanical integration into the vehicle easier, simplify the cooling concepts and reduce electromagnetic interferences. Such arrangement shortens the wire lengths, save space and reduce the voltage loss and power loss.

Various challenges associated with electric vehicle traction inverters and potential solutions are listed in Figure 2.4.

Figure 2.4: Inverter Challenges and Solutions



Achieving higher inverter efficiency can reduce the size of the battery.

The inverter technology for electric vehicles is moving away from silicon insulated gate bipolar transistors (Si-IGBT) to silicon carbide (SiC) devices. SiC based inverters are expected to be further optimized with intelligent control techniques.

2.3 Motor Control System

Electric vehicle motor control involves varying the electrical input power to control the torque, speed and position. The intelligent digital control system integrates, monitors and controls several components of the motor system and does the task of thermal management. The following are its major components.

Sensors: Sensors measure different parameters such as motor speed, motor current, rotor position, battery voltage, and temperature. These sensors provide data to the microcontroller or processor.

Microcontroller or Digital Signal Processor (DSP) or FPGA: The microcontroller, DSP or FPGA processes the sensor data and runs control algorithms that determine the appropriate motor speed and torque based on various inputs. The microcontroller can also adjust the motor speed to the required level by sending signals to the actuator. The microcontroller or microprocessor is the central component of the control system. It receives input signals from sensors, such as throttle position, speed, rotor position, and battery voltage sensors, and uses this information to control the motor speed. The microcontroller or microprocessor also receives commands from the driver through the accelerator pedal or via CAN command, which can be used to adjust the speed and torque of the motor.

Actuator: The actuator is an electronic device that receives signals from the microcontroller or processor and adjusts the speed of the motor accordingly. The actuator can be a motor driver, regulating the current amount delivered to the motor.

Software/ Firmware: The control software runs on the microcontroller or processor and provides the necessary algorithms for speed control. It also includes safety features such as overcurrent, over-voltage, and over-temperature protection. The software running on the microcontroller or microprocessor is responsible for interpreting sensor data, making decisions about adjusting the motor speed and sending commands to the actuator (motor) to make those adjustments. The software can be designed to optimize motor performance and efficiency while also ensuring that the motor stays within safe operating limits.

The control software needs to implement the electric vehicle traction motor operation in the four quadrants – forward motoring, reverse motoring, braking, and generating.

FPGA offers the advantage of speed, flexibility and integrated design tools. They have parallel architecture and have the ability to handle multiple complex algorithms simultaneously in hardware. FPGAs can offer are the ability to use custom pulse-width modulation (PWM), simple component integration, higher control-loop bandwidth, lesser components and higher dependability.

The emergence of the System on Chip (SoC) devices that combine the versatility of the CPU and the processing power of FPGA, has opened up the possibility of consolidating the functionality of the electronic control units (ECUs).

2.4 DC-DC Converter

DC-DC converters should have low losses, high efficiency, low volume, and be lightweight. The development of new DC-DC converters is driven by emerging technologies like high-power WBG semiconductors and bidirectional power supplies.

The DC bus voltages will likely shift from 400 V to higher levels such as 800 V to handle high-power delivery for fast charging [8].

The converters can be unidirectional or bidirectional, isolated or non-isolated, depending upon the requirement.

In battery electric vehicles, an auxiliary isolated DC-DC converter is required to convert high voltage bus to low voltage for 12 V/24 V battery.

The typical efficiency of a DC-DC Converter is more than 96%. The typical power rating of a DC-DC Converter ranges from 1kW to 6kW for a passenger car.

According to the recent reports of the U.S. Department of Energy, by 2025, the technical targets of the 2- to 5-kW DC-DC converter for 12-V low-voltage battery charging are expected to attain high power density (>4.6 kW/L) and high-efficiency (>98%) [2]. A proper topology with an optimized device and passive component design should be deliberated and experimentally verified to achieve this goal.

2.4.1 DC-DC Converter Topologies

2.4.1.1 Non-isolated DC-DC Converters

DC-DC converters in powertrains are generally non-isolated because non-isolated converters have several advantages, such as simple topology, low cost, high efficiency, high reliability, and so on.

To achieve bidirectional power flow, the diodes in the DC-DC converters can be replaced by fully controllable switches, such as IGBT/MOSFET/GaN. Those bidirectional topologies are normally used with an energy storage source, such as a battery or a supercapacitor pack.

Multilevel converters have been proposed to reduce the voltage stress on devices. The multi-level converter can be optimized for various voltage levels suitable for different components of the vehicle, which is otherwise not possible for a single-output converter.

To improve the voltage boost ratio while being non-isolated, a floating interleaved boost converter (FIBC) can be achieved by connecting the upper and lower cells of the classical boost converter.

Based on the specific power-level requirements, a proper topology for the non-isolated DC-DC converter can be selected for different applications, such as on-board/off-board chargers, charging station, and electric power-train.

2.4.1.2 Isolated DC-DC converters

Hybrid and electric vehicles require galvanic isolation to electrically separate the input and output terminals. Safety requirements may dictate using an isolated DC-DC converter—using a high-frequency transformer, particularly if the input side is connected to high voltages to endanger humans. Isolated DC-DC converters are also useful for breaking up ground loops, thus separating parts of a circuit that are sensitive to noise from the sources of that noise. Another benefit of isolated converters is a floating output and level shifting.

The isolated DC-DC converter such as phase shifted full bridge (PSFB), dual active bridge (DAB), and resonant-based DAB, etc., are most common in the EV industry to achieve the above merits of isolation.

The CLLC resonant tank enables the bi-directional power flow.

2.4.1.3 Interleaving DC-DC converters

In the case of high-power applications, paralleling, and interleaving are the options usually adopted to increase the power processing capabilities of the converter stage when a single converter is not capable of handling the required power.

Paralleling or interleaving operations could be helpful in achieving modularity, wide range of power operation, increasing the switching frequency to reduce the filter size and achieving cost-effectiveness. The additional benefit of interleaving is that it eventually reduces the ripple values across the output (load) and input (source). The filter size, i.e., inductor or capacitor size, is reduced.

However, the interleaving operation comes with limitations that a synchronous control operation is required among all the converters. That needs a controller with a large no of PWM pins or real-time communications among multiple controllers. Therefore, the converter's independent or modular operation is limited.

2.4.1.4 Soft switching DC-DC converter

Apart from using low-loss devices, soft switching could be another cost-effective option to decrease the power loss in the DC-DC converters by reducing switching loss. This improves system efficiency and reduces cooling requirements, size, and cost. There are two ways to reduce the switching losses in a converter: ZVS (zero voltage switching) and ZCS (zero current switching) operation.

2.4.1.5 New DC-DC converter topologies:

Several new topologies have been investigated for better utilization of wide band-gap (WBG) devices, better performance, reduction in cost etc. For example, Z-source-network based dc-dc converter can be an emerging topology because it is immune to shoot-through, wide input voltage range operation, and buck-boost operation in single stage are possible.

2.4.2 Challenges and Solutions

Challenges for the DC-DC converter are shortage of semiconductors and maintaining high performance with compact size and minimum cost. These are discussed in Table 2.1.

Table 2.1: DC-DC Converters: challenges and solutions

Challenges	Potential Solutions
High volume and weight	Integrating the On-Board Charger (OBC) and Auxiliary Power Module (APM), i.e., one or two converters from both OBC and APM, becomes common and takes part in charging HV and LV batteries. The other way is the three-port converter (TPC), which has fewer components.
Parasitic inductance at higher switching frequencies result in higher voltage through inductive coupling. Fast changes in voltage may result in high capacitive current transients. The transformer/inductor inter-winding capacitance, gate driver insolation capacitance, and coupling capacitance between the heat sink and PCB can increase common mode noise leading to a false turn-on of the device.	Finite element and Multi-physics simulation analysis to optimize the gate driver and power board layout loop to minimize the inductance. Adoption of novel design methodology for transformer with reduced inter and intra-winding capacitance, less coupling capacitance between the heat sink and PCB, high transient immune gate driver power supply, and gate driver.

Challenges	Potential Solutions
Magnetic components contribute significantly to the volume and losses of the DC-DC converters.	Novel design techniques, new magnetic core materials, and planar transformers to increase the magnetic component efficiency with further reduction in volume and cost. Development of high-frequency magnetic core materials with less loss and high magnetic flux density. Novel integrated magnetic technology that utilizes inter-winding parasitic capacitance for DC-DC converter to reduce the converter volume. The PCB inductor with the spiral winding on a multilayer PCB covering magnetic material.
The increasing demand for ultra-flat converters	Utilization of flat magnetic cores such as planar magnetics, which also results in space utilization and better heat dissipation.
Unwanted high-frequency parasitic resistance, capacitance, and inductance	Optimization of the winding arrangement and structure

2.5 Power Semiconductor Devices

Technology choices for power semiconductor devices include

- ***MOSFET*** (Metal-Oxide-Semiconductor Field-Effect Transistor): MOSFETs are widely used in power electronics because they are efficient and can switch quickly. They can operate at high switching frequencies and are used in motor drives, DC-DC converters, and power supplies. Conventional Si based MOSFET switches have occupied the low-voltage niche. SiC and GaN MOSFETs are more advanced and efficient than Si-based switches.

- ***IGBT*** (Insulated Gate Bipolar Transistor): This is the current choice in high power applications. It has a gate insulated with oxide insulated film, IGBTs combine the Gating characteristics of MOSFET and high current carrying capability of BJTs. Si IGBTs is the predominant semiconductor technology used in electric vehicles. They have high dielectric strength and low on-resistance. They have a high input impedance and low on-state voltage drop, making them efficient and suitable for high power applications such as traction drives. Due to high switching losses and limited switching speeds, the switching frequency of Si-IGBT is limited to around 20 kHz.

Smart Gate drivers having control registers that can be freely programmed to optimize the overall performance and reliability are available today. A fault register is available inside the Gate Driver IC, which helps to identify the faults and the required action to rectify the fault.

2.5.1 Technology Demand

Desired characteristics of power semiconductors: Devices with fast turn-on and turn-off with low on-state power loss are desirable.

Thermal stability. Not only does high temperature destroy devices, but even operation at elevated, non-destructive temperatures can degrade useful life. The maximum junction temperature is typically between 100°C and 200ºC for silicon. Most power transistors have a maximum junction rating of 125°C, the safe operating temperature is much lower.

Transient Effects: Power semiconductors can be destroyed by very short pulses of energy. A major source of destructive transients is caused by turning on or off an inductive load. Protection against these problems involves a careful combination of operating voltage and current margins and protective devices.

Power dv/dt and di/dt: These problems can occur in power semiconductor switches, because all sections of the device do not behave in an identical manner when subjected to very high rates of change.

EMI: Switching power on and off at a rapid rate can cause electromagnetic interference (EMI) that can affect nearby electronic systems. Domestic and international standards define the amount of EMI that can be emitted.

Unclamped Inductive Switching (UIS): Whenever current through an inductance is turned off quickly, the resulting magnetic field induces a counter electromagnetic force (CEMF) that can build up high potentials across the switch. With transistor switches, the full build-up of this induced potential may far exceed the rated voltage breakdown of the transistor, resulting in catastrophic failure.

Cost Considerations: As a semiconductor chip gets larger its cost grows exponentially. And, there is the cost of the package that houses the integrated power device and the cost of interconnections. If an integrated power semiconductor and a discrete power semiconductor have large die, the die cost dominates the overall cost, it would be cheaper to use two parts. Not only does a larger die size mean a disproportionately larger cost, but key parameters may not be the same for all functions of each device on the die.

On-resistance: It determines the power loss and heating of the power semiconductor. Low on-resistance drastically reduces heat-sinking needs in many applications, which lowers parts count and assembly costs.

Maximum junction temperature: TJ(max), is a function of the electrical characteristics of the device itself, as well as the package employed. Package thermal properties determine its ability to extract heat from the die.

Conduction and Switching Losses: Because power semiconductors are primarily used as power switches, they have conduction and switching losses. Conduction losses are determined by the product of operating current and on-resistance of the device. Switching losses depends on how fast the device can switch from on to off and vice versa. The faster the switching speed, the more efficient the device.

Junction-to-case (RθJC) thermal resistance of a power semiconductor can range from 30-50 °C/W for a typical surface mount package, to 2°C/W or less for a TO-220 package.

Electrothermal characteristics and packaging are two important parameters for semiconductor devices.

Packaging of WBG devices: ATMP OSAT, PCB/ SOC Design, Copper/ Silver Sintering. 3-D packaging, new PCB substrate, Integrated SoC design to achieve better thermal management and increased power density Thermal Management.

The desired characteristics of System Requirement of Power Semiconductor Devices in Hybrid, Electric, and Fuel Cell Vehicles are provided in Table 2.2.

Table 2.2: Required specifications for power electronics for EV [9]

Applications	Peak Power Ratings (kW)	Semiconductor Devices	Current Ratings (A)	Voltage Ratings (V)	Switching Frequency (kHz)
Inverters for Propulsion Motor and/or Generator	20-100	IGBTs, Diodes	100-600	600-1200	5-30
DC/DC Voltage Boost Converters for Battery or Fuel Cell Stack	20-100	IGBTs, Diodes	100-600	600-1200	5-30
Inverters for Air Compressors in Fuel Cell Stacks	10-15	IGBTs, Diodes	20-50	600-900	5-30
Inverters for Air Conditioners	2-4	IGBTs, Diodes	10-20	600-900	5-30

The junction temperature of a power semiconductor is the principal determining factor of its current ratings. The maximum continuous current is usually defined as the current that the device can conduct continuously without exceeding the maximum junction temperature. The voltage rating is mainly determined by considering the impact of the commonly encountered over-voltage transients in the automotive environment on the life of these devices. Use of wide band gap devices is preferred even though the devices mentioned above are IGBTs and MOSFETs.

2.5.2 Challenges

Power semiconductor technology is going through a rapid transition and represents the highest-cost item. Power semiconductor devices often dictate the vehicle systems' efficiency, cost, and size. They contribute roughly one-third of the total cost of vehicle power electronics. Based on simulations and assumptions that ultimately electric drive vehicles need to cost no more than IC engine vehicles, the Electrical and Electronics Technical Team of USDrive has set a 2025 cost target of $6/kW for power electronics of a 100 kW vehicle [2]. The currently used silicon-based power semiconductor devices are improving and gaining higher power conversion efficiency. However, technology based on silicon has reached its limitations in terms of desired functions of power electronics converters, such as high voltage blocking capability, operating temperature and switching frequency.

The three-phase AC motors used in today's EVs run at voltages up to 1,000V and switching frequencies up to 20 kHz. This is very close to the operational limits of the silicon-based metal-oxide-semiconductor field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs) currently used in traction inverters. They will have difficulty meeting the higher operational requirements of next-generation EVs.

2.5.3 Solutions

Semiconductor materials having wide band-gap offer several advantages. They can operate at higher temperatures and can dissipate heat more effectively due to their higher thermal conductivity. Since they have higher breakdown voltage, the devices can be operated at higher voltages. Lower on-stage resistance enables high-efficiency operation. Other advantages are faster switching speed, lower conduction and switching on-state loss, and exceptional radiation hardness. High-efficiency performance can be achieved because of low on-resistance characteristics. With high frequency, high efficiency operation the passive components and cooling systems can be downsized, leading to the downsizing of the power electronics systems.

Among the promising candidates, SiC and GaN have entered into the commercial space. Several other WBG semiconductors such as diamond, aluminium nitride, and gallium oxide are presently at the R&D stage.

GaN and SiC technologies are largely complementary and will continue to coexist. GaN devices best used in applications ranging from tens to hundreds of volts (typically up to 650V). Whereas, SiC is better suited for supply voltages from approximately one to many kilovolts.

For the application less than 650 V, the gallium nitride devices are utilized as it offers various advantages like almost zero reverse recovery loss, low on-state resistance, low junction capacitance and low gate charge. However, at voltages beyond 650V and currents beyond 50 A, GaN devices are expected to remain more expensive as compared to equivalent SiC devices. SiC has some product availability at 650V, but is generally designed for 1200V and higher.

A 900V, 10mΩ SiC MOSFET rated for 196 A of continuous drain current at a case temperature of 25°C was claimed to enable the reduction of EV drive-train inverter losses by 78 percent based on EPA combined city/highway mileage standards.

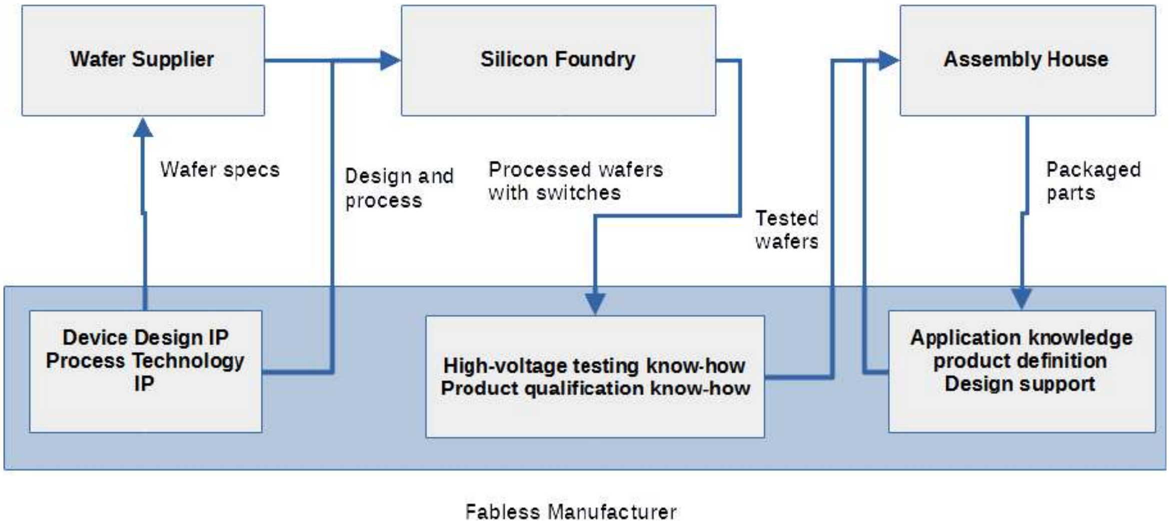
However, due to complex crystal growth chemistry and low-scale production, the single crystal substrate wafers of GaN or SiC are costlier as compared to Si. In case of the SiC, the biggest contributor to the cost is the SiC substrate itself. The seeded sublimation process used for crystal growth is slow and energy intensive as compared to the choleski process used in case of Si. Apart from this, both epitaxy growth and SiC device fabrication require higher temperature and are costlier as compared to processes involved in case of Si, although the difference is not as much as in case of substrate costs.

Another emerging WBG semiconductor option Gallium Oxide (Ga_2O_3) can potentially address the cost-performance trade-off.

Only few players in the world are into the semiconductor fab business. Semiconductor manufacturing is a complex process comprising of numerous processes steps.

Fabless manufacturing is also one established business model (Figure 2.5). Although fabless manufacturing is a low-investment option, development of competency in semiconductor fabrication is extremely important and the Government of India has initiated the India Semiconductor Mission with this objective.

Figure 2.5: Fabless Manufacturing



The R&D issues associated with the manufacturing and application of WBG semiconductors in electric mobility are listed in Table 2.3:

Table 2.3: R&D issues for WBG semiconductors

Issues	R&D Need
Design	New process for GaN bulk crystal growth with higher speed and quality. GaN bulk crystals are difficult to obtain by conventional melt solidification crystal growth processes.
Manufacturing	Investment in new manufacturing equipment
Stress and high defect densities in GaN devices due to epitaxial growth on the non-native surface	Alternative epitaxial approaches
Module and packaging	Improving high voltage insulation, thermal management, partial discharge, and EMI to enable high-performance modules high-performance discrete packages that can operate at higher temperatures and voltages. New layouts, gate drive and construction techniques to handle EMI/ EMC issues
Surge voltage	To adopt soft-switching techniques. Soft-switching technique requires additional soft-switching circuits including resonant inductors, resonant capacitors, and active switches
Reliability	Understanding the materials defects that can occur during the manufacturing process. Gaining a better understanding of degradation/failure mechanisms under harsh conditions
Simulation tools	Ability to simulate complex operating modes and fault conditions
Test/ characterization	Need for new measuring equipment – high voltage probe along with high voltage probe compensation reference circuit; creation of structures to allow use of high current, high bandwidth current sensors

2.6 Passive Devices

Passive devices include DC-Link Capacitors, Ferrite Inductors, Resistors, Transformers etc. These devices can only receive energy and dissipate, absorb, or store in an electric or magnetic field. In automotive applications, the passive devices should withstand vibration and high temperature. They should be highly reliable, compact, and have better thermal management.

Areas for development for the passive devices include cost reduction, enhancing performance, functional integration and manufacturing process and equipment.

Passive elements and thermal management contribute most of the volume and mass of the power electronic converters. The requirement of the inductors can be reduced with high-frequency WBG devices. However, it is essential to develop WBG Compatible Passive Devices. Required characteristics of various passive devices for use along with WBG semiconductors are summarized in Table 2.4.

Table 2.4: Required characteristics of passive devices

Device	Required characteristics
Capacitors	Capability to operate at temperatures up to 125/ 130°C High power density, high current handling capability Low inductance High frequency Soft Termination Capacitors Low ESR
Magnetics	Magnetic core materials with better temperature stability Enhanced saturation limits for inductors and transformers High frequency magnetic cores (up to few MHz) Reduces winding losses in transformers Lower tolerance resistor in sensing applications
Resistors	Lower inductance Thick Film technology for higher power densities Improved thermal management
Laminated Busbars	Glues should be able to withstand temperature up to 105°C New isolation materials

New substrates and magnetic materials offering high power density and high temperature tolerance are desired.

2.7 EV Battery Charging Systems

EV batteries are charged from various sources having different specifications like household supply (240 V) or DC fast charging station (420V).

EV chargers comprise various AC and DC power converters. The charging speed depends on the converter capability and output power level of the charging point. DC chargers require high power, specific components, safety protocols, and large power control circuits.

2.7.1 On-Board Chargers

Electric passenger vehicles are usually equipped with an on-board charger that converts the AC power received from the grid into DC and charges the traction battery. A few electric bus models also have on-board chargers. The desirable characteristics of electric vehicle on-board chargers are high power density and high efficiency. The reduction of weight of the on-board charger contributes toward increasing the range of the electric vehicle. It needs to be compact, as a vehicle always has space constraints. Thermal management of the on-board charger is another important issue. The OBCs need to be compatible with the smart grids, and the ability to allow the bidirectional flow of power will enable the implementation of technologies such as vehicle-to-grid or vehicle-to-home.

On-board chargers for passenger car are typically rated for 3.3kW for operation from a single-phase power source and goes all the way to 22kW for operation from the 3-phase power source. The typical efficiency of Onboard Chargers is more than 95%, which is expected to reach better than 97% in coming years. Typical power density of Onboard Chargers is less than 1kW/Lit. In the coming years, the power density of onboard chargers is expected to improve to 3kW/Lit.

Electric vehicles with dedicated on-board chargers have two different converters – AC/DC converter for battery charging and DC/AC converter (inverter) for motor control. On-board chargers typically comprise

- EMI Filter
- AC/DC converter; Power Factor Correction (PFC) circuit to reduce harmonics
- Isolated DC/DC converter.
- A large capacitor between the two converters to filter grid frequency
- The modern trend is to use interleaved (parallel) topologies of the DC/DC converter that feeds to the battery.

The use of bidirectional converters becomes relevant in the context of vehicle battery pack supply power for external applications. Vehicle to Home (V2H) and Vehicle to Grid (V2G) technologies are also being pursued. However, supporting bidirectional power flow for such applications requires a complex control system, high capital cost, and involves energy loss and stress on the devices. It may also result into faster degradation of the battery.

WBG-based on-board chargers may enable higher power density and efficiency.

The output voltage of the on-board charger is limited by the battery pack voltage. Hence it is impossible to draw very high power from the grid for a feasible size of the on-board DC/AC converter. On-board chargers involve extensive safety requirements at the high power levels and contribute to the size and weight of the vehicle.

High charging time resulting from low power transfer is a major drawback for on-board chargers. Consideration of volume, cost, and weight are major challenges to implementing high power on-board chargers. A concept that emerged from the efforts to address this issue is that of the integrated chargers.

2.7.2 Integrated On-Board Chargers

The idea is to use a single AC/DC converter to control the motor and charge the battery. Such chargers can support bidirectional power flow while consuming smaller space compared to conventional systems. Valeo [10], TM4 [11] have developed such technology,

2.7.3 DC Charging of EVs

Establishing a DC-only charging ecosystem can potentially reduce the complexity of the charging systems of electric vehicles. However, consensus will be needed among various stakeholders and the development of appropriate regulations and standards. This issue has been discussed in detail in *Volume 4: EV Charging Infrastructure*.

It is anticipated that low-power DC chargers may bring several benefits to the EV ecosystem in India. Low power wall-mounted DC chargers (up to 30 kW) are expected to be similar to the AC chargers in cost, installation space, and design complexities. Protocols for higher power DC-chargers are already established globally and in India too, DC charging standards from 50 kW to 200 kW have been defined.

Most of the off-board charging topologies use high frequency transformer (50 kHz – 300 kHz) to achieve galvanic isolation in the DC-DC converter stage for safety, better control of voltage adjustments, and compactness. Modularisation is a trend in the design of chargers to achieve compatibility, high efficiency, and economic benefits. The concept of Power Electronics Building Blocks has been accepted widely in design of off-board chargers.

2.8 Power Electronics: Key Points

Electric Vehicle power electronics is evolving to a stage wherein conventional silicon based power semiconductor devices have reached their limits, and use of WBG semiconductor is expected to gain more and more importance. A necessary step towards this is the design of the passive components, converter topologies, and thermal management to reap benefits of WBG semiconductor. Packaging of WBG semiconductor devices needs attention. Development of various topologies for inverters and DC-DC converters with higher power density, high temperature operation and high switching frequency has been a major focus of power electronics for electric vehicles in recent times. Optimization of the fabrication of WBG semiconductors is an essential step for modern power electronics ecosystem. India needs to develop competency in fabrication of power semiconductor devices.

Development of appropriate control systems for effective functioning of the power electronics systems in the electric vehicle is another critical issue, particularly in the context of power electronics with WBG devices.

03

TECHNOLOGY PRIORITIES IN TRACTION MOTORS

3.1 Introduction

The desired characteristics of the electric vehicle motor are high power-density, high torque-density, wide speed range, high efficiency over a broad torque speed spectrum, reliability and robustness over the entire life cycle, reasonable cost, low noise, and small size. Electric vehicle motors can be designed to operate at a more comprehensive speed range, eliminating the need to use a variable gear system to operate efficiently. A motor with a larger field weakening region can provide good performance for electric vehicles in both high-speed highway driving and low-speed city driving. All these pose unique challenges for design and manufacturing for EV motors.

Indigenous design and manufacturing of electric motors and the development of its supply chain are critical steps towards overcoming hindrances to electric mobility in India. in India, competency on electric motor manufacturing has been largely limited to high-power AC motors for railway traction, AC & DC motors for appliances, motors for pumps, fans, etc. However, with a recent focus on electric mobility, some companies, have come forward to manufacture motors suitable for electric vehicles of various types. Some OEMs like Ola Electric have also been engaged in the design of motors for their own vehicles. For the development of competency in the entire supply chain of electric vehicle motors, focus is required on simulation and design, precision manufacturing, and development of materials for motor components/ subcomponents.

The manufacturing process and, mainly, materials requirement depend on the choice of the motor topology.

3.2 Motor Topologies Used in EVs

Numerous conventional and emerging motor topologies exist, and the appropriate choice of traction motor for EVs may vary based on specific usage profiles or other considerations.

- **Light EV**

Brushless DC (BLDC) motors are widely used for EV two-wheeler and three-wheeler applications due to their simple manufacturing since the number of poles is lower, simpler control and sensing due to the simplicity of the stator current waveform, and thus lower cost than Permanent Magnet Synchronous Motors (PMSM). Many of these BLDC motors are hub motors. Centrally-mounted motors are also used in three wheelers and some e-bikes. These are also capable of regenerative braking. Due to the presence of PMs, iron losses happen irrespective of load and with cheap stampings can cause rotor losses and heating at high speeds which could lead to magnet performance degradation. These are typically cooled by natural convection due to the motion. Switched Reluctance Motor is also considered a suitable candidate for electric 2/3 wheelers.

- **Passenger Cars and SUV traction motors**

Permanent Magnet Synchronous Motors (PMSM) are the most popular motors in the segment. Non-REPM motors like Synchronous and Induction motors are also popular in this segment. Variants of SRM may be suitable for passenger cars, too. These are typically liquid cooled.

- **Commercial EV traction motors**

3-phase AC induction motors have high penetration in this segment due to their lower cost and long life due to low maintenance. However, PMSMs are also gaining attraction in this segment. These are also liquid cooled.

There is a need to advance the design and manufacturing of standard motor types for EV applications like PMSM and BLDC. There is also a need to develop indigenously sustainable RE magnets, magnets with alternate materials and electromagnets. Apart from these the R&D needs to focus on configurations without REPMs like SRM, SynRM and IM as well as hybrid configurations that use a reduced quantity of REPMs.

3.3 Supply Chain for EV Motors: Materials

Strategies to address the supply-chain uncertainty of rare-earth permanent magnets could be many-folds:

- More abundant materials, such as Cerium, could be utilized to replace rarer elements, such as Dy or Tb. Grain Refining or Grain Boundary Engineering may play an important role in developing such technologies.
- Reduce rare earth content. Hitachi has adopted a new process featuring diffusion of Dy into the magnet material instead of alloying. Another approach involves using alternative materials and reducing the grain size of the magnets to a nanoscale level to achieve a similar maximum energy product.
- Develop machine topology that requires less rare earth magnet (e.g., Hybrid Motor)

3.3.1 Motors without permanent magnets

Induction motors, synchronous reluctance motors (SynRM), and switched reluctance motors (SRM) do not use permanent magnets. Research is underway to improve their performance.

AC Induction motors have been used in electric vehicles (EVs) as they are reliable, offer improved efficiency compared to brushed DC motors, and have low maintenance requirements. This is important particularly for high power commercial vehicles. Since rotor current cannot be directly controlled, although using advanced control techniques torque can be controlled, the torque response is slower. However, fast torque response is not a priority for CVs. Since it draws additional current for rotor excitation, the overall motor efficiency is lower compared to the BLDC/PMSM motor. To reduce losses, use of copper and aluminium for rotor conductors are options. However, induction motor remains a candidate for EVs, particularly in the context of concerns over the supply of magnets.

3.3.2 Motors with permanent magnet assist

Permanent Magnet Assisted Synchronous Reluctance Motor (PMASynRM) using inexpensive and readily available Ferrite permanent magnets has also been explored.

3.3.3 Reducing the cost and quantity of RE

Studies suggest that PM motors' structural design and chemistry changes can reduce their RE content. On a design level, introducing an asymmetrical, less rare earth permanent magnet motor (ALREPMM) is expected to reduce the RE component.

3.3.4 Use of alternative permanent magnets

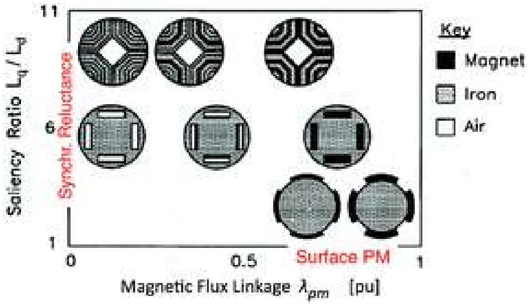
Besides ferrite magnets, Aluminium-Nickel-Cobalt (AlNiCo) magnets with exceptional thermal characteristics and high corrosion resistance may be explored for PM motor production. Like ferrite magnets, these also require structural innovation to reduce the risk of demagnetization. Further, the potential of Cerium Cobalt ($CeCo_3$ and $CeCo_5$) magnets and paramagnets can be explored for future motor production.

Another alternative technology is the development of highly coercive nanoparticles for performance similar to REPMs. The researchers from LPNCO France have developed Cobalt nanorods with exceptional coercivity- reportedly much higher than AlNiCo- that can be used as RE-free magnets with properties approaching Neodymium based formulations.

Research directions should also focus on developing artificially synthesized rare-earth-free magnets. An example in this regard is the iron-nickel crystal structure, found naturally only in asteroids, being developed under an ARPA-E project [12].

Figure 3.1 shows various types of PM motors and their position in saliency ratio-PM flux linkages. Torque developed by the motor depends on these two parameters. Research should concentrate on improving the saliency ratio which increases the reluctance torque while optimizing the magnet utilization.

Figure 3.1: Types of PM Motors and their position in Saliency Ratio – PM flux linkage plot



Source: Soong and Miller, 1994 [13]

3.3.5 Magnetic Materials

Various types of permanent magnets are listed in Table 3.1. Ferromagnetic materials form the core of stator and rotor of electric motors. They can be broadly divided into two categories: soft magnetic materials and hard magnetic materials.

A soft magnetic core gets magnetized when field excitation is applied. These materials are also used in the rotors of induction, SRM, and SynRM motors.

Table 3.1: Various Types of Permanent Magnets [14]

Type of Permanent Magnet	Typical Composition	Advantage	Disadvantage	Research Focus
AlNiCo	Aluminium, nickel, cobalt, iron (copper/ titanium/ zirconium/ silicon -iron)	High remnant magnetic induction Retain magnetism at high temperature	Low coercivity, may get easily demagnetized	Improvement in coercivity
Ferrite (also known as Ceramic magnets)	Ferric oxide (may include strontium and barium too)	High electric resistivity Inexpensive, easy to produce Coercivity increases with temperature	Low remnant flux density (1/3 of NdFeB) Low coercivity (1/5 to 1/3 of NdFeB)	Improving remnant flux density. Flux-focusing. Better motor design to withstand field weakening
Samarium cobalt	Samarium, cobalt (may also include zirconium and iron)	Retains magnetic flux at high temperatures. Sm2Co17 can operate up to high temperature of 500oC. Maximum energy product up to 240 kJ/m3	More expensive than NdFeB	Enhancing energy product Cost reduction by replacing cobalt partially by iron and nickel.

Type of Permanent Magnet	Typical Composition	Advantage	Disadvantage	Research Focus
Neodymium iron boron	Neodymium (dysprosium, praseodymium or terbium may be added)	Energy product up to 450 kJ/m3 has been achieved	Uncertainty in supply Demagnetization at high temperature	Alternative to Dy or Tb that are used for enhancing temperature tolerance

Saturation magnetization, often referred to as magnetization, is the density of magnetic moments within a ferromagnetic material. A higher value of magnetization enables a material to produce a higher external magnetic field per unit mass.

The EV/HEV traction motors should resist a high demagnetizing field at temperatures above 180°C.

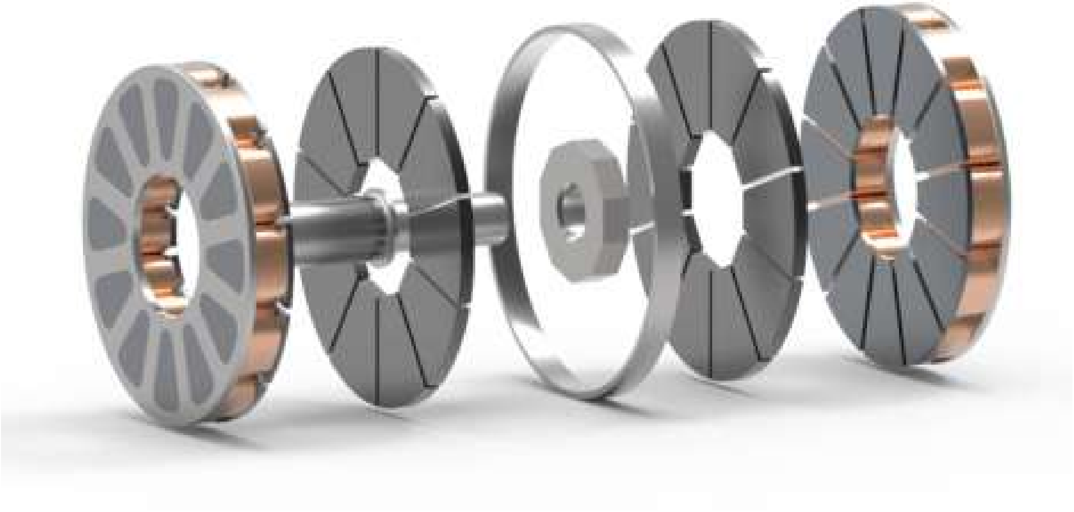
Iron loss in motors depend on the operating frequency and operating flux density. For a given value of flux density, iron loss increases with frequency and therefore, the speed. So, it is desirable to have appropriate soft magnetic material that can reduce the iron loss. High-silicon electrical steel and amorphous alloys are some of the magnetic materials being explored in this regard.

3.4 Topologies to Enhance Torque Density and Efficiency

3.4.1 Axial Flux Motors

In this configuration, the magnetic flux flows in the axial direction. These machines are preferred in machines having high outer diameter to stack length (D/L) ratio. Due to the shorter magnetic loop, the torque density of an 'axial flux motor' is higher compared to radial flux machine. The absence or lower mass of the stator core reduces the eddy current losses, leading to improved efficiency. This design also helps to stack many stators and rotors in parallel to multiply the motor power as shown in Figure 3.2. Some of the challenges in this design are air gap maintenance and cooling of stators. Various designs are proposed to overcome these limitations, making the axial flux machine more attractive. Another important factor is that the output torque increases significantly with the increase in the diameter. A typical axial flux motor is shown in Figure 3.3. However, further R&D is needed to adapt and develop such motors for the EV powertrain environment.

Figure 3.2: Multi-stator multi-rotor axial Flux PM Motor



Source: Miba AG [15]

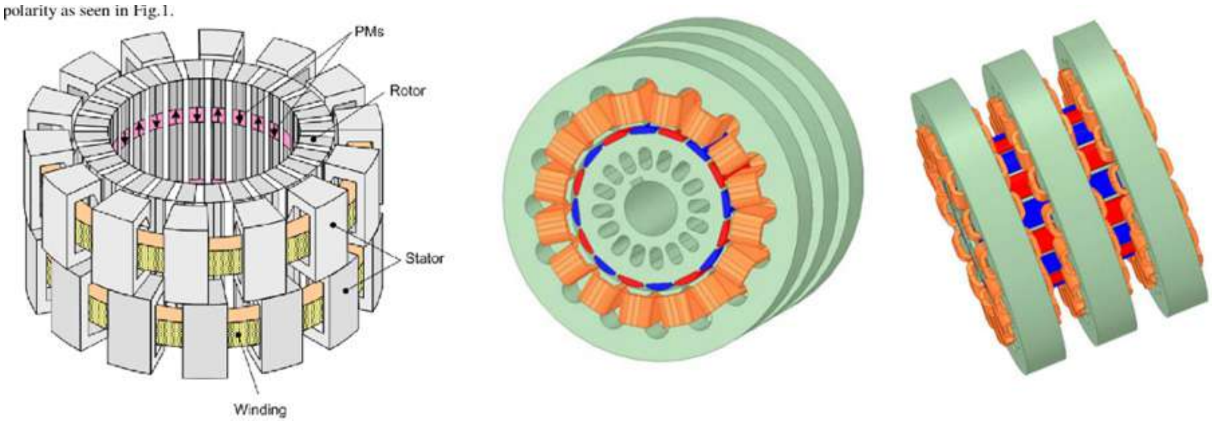
Figure 3.3: Axial Flux motor

Source: YASA Motors [16]

3.4.2 Non-Rare Earth Transverse Flux Machine

A transverse flux machine (TFM) is an emerging machine with potential application in electric vehicles. In these machines, coils are wound circumferentially around the axis of rotation. This setup enables the 3D flow of magnetic flux, which crosses axially through the stator, circumferentially through the rotor, and radially through the gap. These machines, still at an early stage of development, have high torque density and may be suitable for direct drive applications. Figure 3.4 shows a schematic diagram of a typical transverse flux motor.

Figure 3.4: Schematic diagram of a typical Transverse Flux Motor



Source: Drabek et.al., 2021 [17]

They have a "Ring" shaped winding, which couples each stator core to the entire armature ampere-turns. High torque can be achieved by increasing the pole numbers without sacrificing electric loading. Such machines might offer high power density and high efficiency. However, R&D efforts are required. The major challenges involve high leakage flux, low winding utilization and complex structure.

Table 3.2 compares the three different topologies (RFM, AFM, and TFM) regarding various parameters.

Table 3.2: Comparison among RFM, AFM and TFM

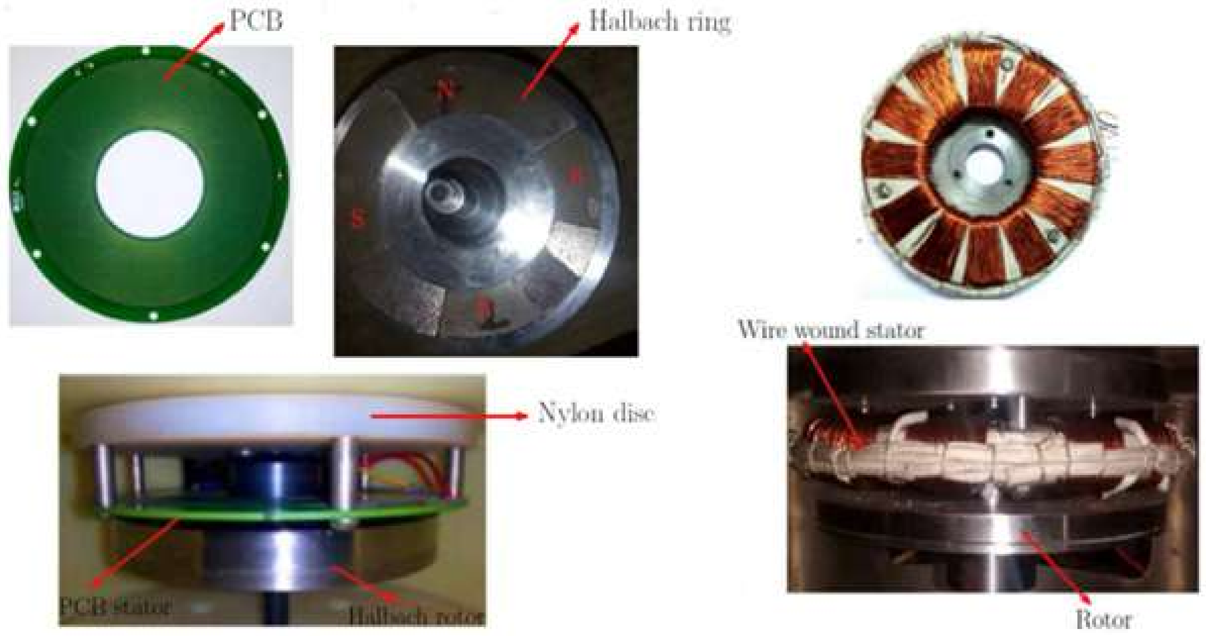
Parameter	Comparison
Efficiency, power density and torque density	The shorter magnetic path of the AFM contributes towards efficiency and power density of the machine. TFM can have higher torque density
Application	AFM topology is suitable for applications with limited axial length. Since TFM can accommodate a higher number of poles, it may be an attractive alternative for high-torque and low-speed applications. It is suitable for direct-drive applications because of its high torque density.
Thermal Management	In the case of RFM, the heat is evacuated through the stator core made of steel that has a low thermal conductivity AFM has higher active copper winding with less overhang. This enables an increase in the number of turns and reduces heat generation caused by the end effect. Also, the winding can be in contact with aluminium, which is a good heat conductor. This results into an easier cooling system.

Parameter	Comparison
Manufacturing	The manufacturing process of RFM is simpler and involves straightforward lamination stacking technique. Manufacturing of AFM requires more complex engineering and careful considerations to achieve cost parity between the two technologies TFM is generally considered difficult to manufacture, too complicated, and thus too expensive.
Design and Simulation	For RFM, 2D simulation is sufficient for the electro-magnetic design. The electromagnetic design of AFM requires 3D simulation, which requires powerful hardware

3.4.3 PCB Motors

R&D efforts are underway to make the Stator and Rotor as Printed Circuit Boards and operate as axial flux motors. Due to its construction, the weight and size are very competitive, but the reliability to operate in automotive applications and environments needs much more research. A typical axial flux PCB motor is shown in Figure 3.5.

Figure 3.5: PCB Motor Parts and Assembly

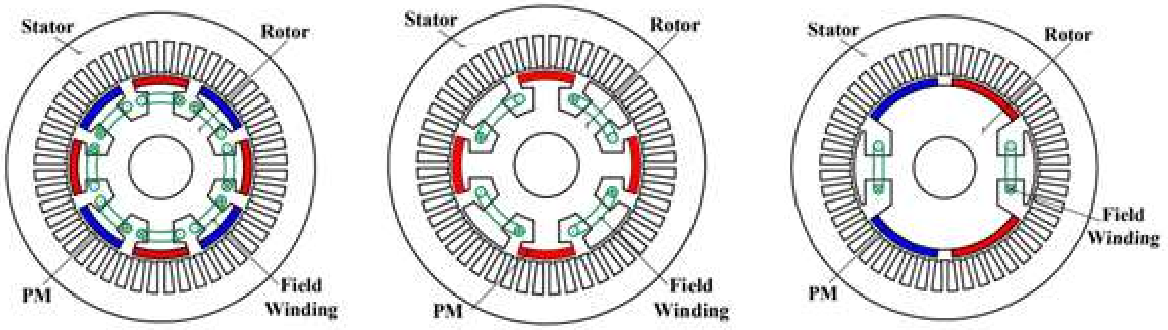


3.4.4 Other Promising Technologies

In addition to the disadvantage of use of rare-earth materials, permanent magnet synchronous motors (PMSMs) also suffer from limited overloading capacity and complex and less reliable field weakening. These result in limited acceleration and starting torque, less reliability and higher cost. All these problems are taken care by electrically excited synchronous motors (EESMs). These motors provide convenient and reliable field weakening with wide CPSR. They also have the provision to overload the motor from stator and rotor sides. However, motors with larger number of turns in the field winding are less power dense and less efficient compared to PMSM motors. So their size and weight are more than PMSMs.

An electric machine having the advantages of both a PMSM and an EESM is a very attractive solution for electric vehicle applications. The PMs increase power density and EE field winding enhances capability, reliability and ease of field weakening. Such a machine having both permanent magnets and field winding in rotor is called hybrid-excited synchronous machine (HESM). It has several advantages including high torque density, high efficiency, high overload capacity, improved starting torque, reduced use of rare-earth materials, easy and flexible field weakening operation with wide CPSR, better reliability and an additional degree of freedom (hybridization ratio) to locate the maximum efficiency point at desired operating region depending on specific drive cycle. Figure 3.6 shows the typical HESMs.

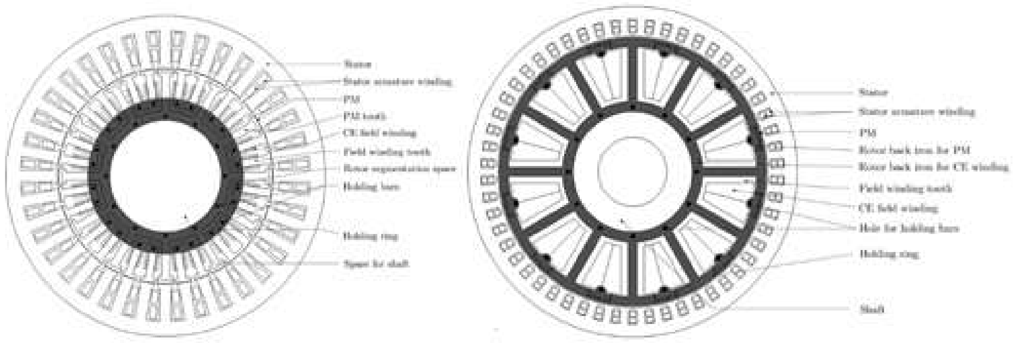
Figure 3.6: Various configurations of Hybrid Excited Synchronous Motor



Source: Zhu, 2019 [18]

The latest addition to the HESM family is completely hybridized, truly parallel, segmented-rotor HESM (Figure 3.7) with better efficiency, torque density, reliability and cost effectiveness.

Figure 3.7: Completely hybridized, truly parallel, segmented-rotor hybrid-excited synchronous motor



The problem related to EESM and HESM, use of sliding contact-based technology to supply the field winding in rotor is, possible to overcome with wireless power transfer technology. Rotating transformer-based brushless operation technology shows promising performance. The latest addition to this technology allows to control the field current in the rotating field winding in both positive and negative magnitudes from the stationary part only and without applying any wireless communication like Bluetooth. This results in smaller field winding in rotor for the same nominal ratings and hence increase in efficiency, torque density and reliability.

3.5 Various Motor Topologies – Challenges and Potential Solutions

Each motor topology discussed above is associated with some challenges that need to be addressed. Table 3.3 outlines some of the challenges and potential solutions.

Table 3.3: Issues in motor topologies that require R&D focus

Challenges	Potential Solution
Induction Motor	
Low efficiency – rotor, mechanical, and stray losses	Enhance conductivity - use of copper cage rotor Increase model calculation accuracy with 3D finite element analysis Control technology with iron loss model Structural design to enhance efficiency Keep the stator temperature under control
Low power density	Improved conductivity and conductor density (e.g., use of copper cage rotor and high fill factor stator) Integrated motor-inverter
Faults occurring at the bearings and insulation materials	Study the physical and chemical properties responsible for the failure Use higher grade enamel, varnish/potting material in the stator. Use high-grade, high-temperature grease in the bearing. [19] Use higher-class sealing in the bearing. Use a shaft grounding ring to reduce electrical erosion in the bearing. Proper creepage and clearance distances should be provided in the design to handle high voltages.
In the case of light electric vehicles, the motor current is high, and the motor has a high loss and temperature rise.	Copper cage rotor Decreasing air gap length Mechanical processing required to decrease air gap length Better stator cooling design Thermal modelling and optimization

Challenges	Potential Solution
Permanent Magnet Synchronous Motor	
Demagnetization at higher temperatures, causing reduction in torque and efficiency	Development of demagnetization fault detection method and demagnetization prevention algorithm Motor thermal management Temperature based de-rating strategy. Rotor cooling with hollow shaft design. Use of higher temperature grade magnets.
The availability and price of rare earth materials are a concern.	Development of alternative magnets with similar properties Development of alternative motor topologies and improve their performance to match that of PMSM
High cost	Develop indigenous manufacturing competency, along with the equipment required to manufacture Development of technology for the production of magnets with Indian rare earth materials or raw materials sourced from outside Enhance power density to reduce materials cost. Power density may be increased by higher speed, better thermal management, or higher fill factor of windings Development of rare-earth free and low-cost permanent magnets with adequate energy density and coercivity. Novel topology such as flux memory motor may improve the performance of motors with AlNiCo magnets Design an effective cooling strategy to reduce the temperature grade of the RE magnets. V or double V magnet topology to minimize the quantity of the RE magnets. Integral controller to reduce the interconnection cost
Rotor position sensing Unreliable position signal from Hall Effect Sensors during start and low-speed operation. ABZ encoder and differential ABZ encoder require more output channel	Sensors based on Resolver (rotary electrical transformer) are used, but need to be adapted for each type of synchronous motors specifically Inductive sensors standardized for all motors have been developed

Challenges	Potential Solution
Switched Reluctance Motor	
High torque ripple, high noise, and vibrations. Control is challenging due to non-linear characteristics.	Structural design, material choices Novel topologies regarding the number of stator/ rotor poles, pole shape etc. Advanced control methods: current and angle modulation, torque sharing function (TSF) control, optimized power topologies
Low torque density	Use of high saturation flux density material New topology such as axial-flux SRM Optimization of axial length, stator shape and winding width Optimization of the shape and number of stator/ rotor poles
Auditory noise	Improvement in stator/ rotor topology to reduce radial vibration Independent control of pole currents Randomizing turn-on/ off angle
High torque ripple	Optimization of a number of stator/ rotor poles along with stator/ rotor pole arc angle, winding connection electromagnetic performance, etc. Pole shape design Optimization of switching angle and current Torque sharing function (TSF) control
Availability of controller to tap its full potential	Development of high-current high-power controller
Synchrel Motor	
Lower specific (peak) power and specific (peak) torque	Increasing rotor operating speed and flux weakening region. This needs to be done to maintain the mechanical integrity of the rotor. Optimized rotor design Axial Flux PM Motor and PM Assist Synchronous Reluctance Motor may improve the torque density, and it is possible to use ferrite magnets.
Availability of controller to tap its full potential	Development of high-current high-power controller
Hybrid Excited Synchronous Motor (Figure 3.7)	
Use of sliding contact-based technology to supply the field winding in rotor	Wireless power transfer technology Rotating transformer-based brushless operation technology

Challenges	Potential Solution
Magnetic Geared Electrical Motors	
High torque density	The magnetic geared motors can offer very high torque density resulting in a compact power dense motor that saves onboard space of the vehicle that can accommodate a larger battery.
Fault tolerance	Replacing a mechanical gear with its magnetic counterpart results in superior fault tolerance as the magnetic gear is invulnerable to overload.
Less maintenance	Replacing a mechanical gear with its magnetic counterpart results in reduced maintenance downtime and cost as magnetic gears facilitate contactless mechanical energy transfer.

3.6 Motor Health Monitoring

The electric vehicle motor is a complex system comprising mechanical-electrical-magnetic-thermal coupling system. Such a complex internal operating environment, limited space availability, and the poor heat dissipation conditions make them prone to failure. This in turn may result into degradation of overall performance of the electric vehicle. For example, PMSM may be associated with faults such as rotor eccentricity, permanent magnet loss, phase loss operation, and winding interturn short circuit. Due to manufacturing defects, the mechanical angle may differ from the design value. In case of multipole machine, this difference is amplified for the corresponding electrical angle. Such faults affect the power, stability, and safety of the vehicle.

Condition monitoring of electric machine comprises online signal monitoring, detection of signal anomalies and appropriate prognosis. The sources of the sensed signals may be electrical, mechanical, thermal, etc. The signals are sensed continuously to monitor a running machine and check for any deviation from normal operation. The sources of different signals are as follows:

- Electrical: Current and voltage.
- Mechanical: Bearing vibration, machine body vibration, vibration due to eccentricity, etc.
- Thermal: Machine body heating.

Online machine health monitoring allows for fault detection during the incipient stage and provide early warning to the user. Early detection and prognosis can improve safety, limit the extent of damage, reduce down time and repair expenses. A typical condition monitoring schemes are shown in Figure 3.8 (a) and (b).

Figure 3.8 (a) Vibration Monitoring and (b) Condition Monitoring Schemes

Source: G3SoilWorks, www.geologyengineers.com [20]

3.7 Motor Manufacturing

Electric vehicle motors can be manufactured using several methods, depending on the specific type of motor and the desired performance characteristics. Here are some common manufacturing methods for electric vehicle motors:

3.7.1 Stator and Rotor Core Construction

An electric motor's stator and rotor cores are typically made from laminated steel sheets, which are stacked together to form a magnetic circuit. These laminations reduce energy losses due to eddy currents, and the stacking orientation can be optimized for specific performance requirements. The sheets are often coated with a thin insulation layer to reduce the flow of eddy currents.

The established process for lamination includes stamping, slinky or blanking, and then laser welding, and sticking technology. Since all these processes affect the magnetic properties of the stack, there is a growing interest in the technology of laser welding electrical laminations. The laser welds tend to be small and have less influence on the magnetic properties of the stacks.

Moreover, the classic interlocking system is less reliable as the thickness of the laminations decreases. The laser welding technology has a lot of promise, particularly for high-end products. It is energy efficient and ensures satisfactory mechanical properties of the welds.

In general, two techniques for laser welding are currently in use: (i) continuous-laser welding and (ii) pulsed-laser welding, with a large degree of overlap. Some studies have found that a pulsed-laser welding system reduces the volume of molten material

With the trend towards compact and efficient motors, advanced adhesives will play an important role in the joining processes in the manufacturing of electric vehicle motors.

3.7.2 Winding assembly

The stator winding, which generates the magnetic field that drives the motor, is typically made from insulated copper wire. The wire is wrapped around the stator core in a specific pattern which depends on the type of motor. In the case of the winding, the assembly process should be automated using machines that wind the wire onto the stator core.

The shape and arrangement of the windings influence the torque density, power density, and efficiency of the electric machines. They should be extremely dense and should not have any inaccuracy. An increase in the slot-filling factor and keeping the winding heads as low as possible is a key thrust for the winding technology for higher efficiency of electric motors.

Considering the trend towards higher operating voltage of the motor, it is necessary to ensure the insulation of magnet wires corresponding to the interphase voltage at the coil end.

Traditional windings used round-wound wires and initial efforts to improve fill factor focused on ortho-cyclic layered winding methodology and the pressing tooth-wound. Various winding methods include:

- Distributed winding method of round wires
- Concentrated winding method of rectangular wires for in-situ as well as for insert winding
- Distributed winding method for rectangular wires

The recent trend is rectangular hairpin winding methodology, which has the advantages of less complexity, higher possibility of mass production, maximizing current density, shorter end-winding and lower DC copper losses. Hybrid and electric vehicles such as Toyota Prius and Chevrolet Volt/ Bolt has used this technology. Whereas with the conventional round wires fill factor is within the range of 0.4-0.6, it is possible to achieve fill factor of about 0.75 with the hairpins [21].

For electric vehicle motors with high voltage, high current and high speed, winding design with parallel paths is essential.

Research efforts have explored new manufacturing process of winding bars.

Another emerging approach is reconfigurable winding with interior permanent magnet synchronous motors. Since the torque producing current in the field-weakening mode of the motor is reduced, resulting in reduced torque at higher speeds, the idea is to use serial windings at low speed and then reconfigure them to parallel windings at higher speed.

Thermal consistency of the used material has an impact on the continuous power density of an electric machine. Increase in the thermal conductivity of the winding enables improved cooling of the motor, allowing production of additional power. Development of winding topology that enables easier heat dissipation may contribute towards achieving higher power density as well as safety. Potting of the stator winding helps to dissipate the heat much faster and enables to operate more efficiently, making the motor more durable even at higher power.

Other than the traditional stator cooling method, some high-end designs use direct oil spray over the stator end winding which helps to reduce the temperature significantly, thereby improving the performance and durability.

Various insulation materials used in electric motors include mica, polyamide-imide (PAI), polyester, epoxy etc. PAI is mostly used in the form of an enamel coating on conductor wires which form the machine windings. PAI has a good high temperature performance.

Modelling of the winding methods and corresponding motor losses and performance will help in the process of design of appropriate traction motors for various categories of Indian vehicles. Development of machinery for advanced winding methods and corresponding equipment for inspection and verification will help in higher domestic value addition and enhancement of competency in the electric motor value-chain in the country.

Manufacturing of the stator winding must result in uniform phase winding which gives same phase resistance and inductance. This results in balanced sinusoidal waveform from the stator phases and hence gives much quieter and best performance.

High potential (HIPOT) test must be carried out to ensure the insulation capability of the stator- assembly. Surge test that compares with the master curve needs to be used to ensure the overall quality of the stator core and consistency of the copper winding.

A common problem, high cogging torque, can be reduced by skewing the stator stack.

To reduce the manufacturing complexity, segmented stator core may be used which can be joined to form a full circle. The segmented core simplifies the stator winding like bobbin assembly and enabling a higher copper fill.

3.7.3 Magnet assembly

The permanent magnets used in the rotor of a PMSM/ BLDC electric motor can be made from various materials, including neodymium, samarium-cobalt, and ferrite. The magnets are typically moulded into a shape that matches the rotor core and then attached to the core using adhesive or other methods.

Care has to be taken to ensure the right polarity magnets are assembled at the right location. Rotor balancing is critical to have better NVH performance. Runout and perpendicular alignment of the shaft are critical to ensure uniform airgap without rubbing on the stator at higher speed operation.

3.7.4 Casting and moulding

Some electric motor components, such as the rotor or stator housing, can be cast or moulded using various materials, including aluminium, steel, or composites. This allows for more complex shapes and can reduce the number of parts that need to be assembled.

3.7.5 Machining and finishing

Once the individual components are manufactured, they are often machined to precise tolerances and finished with coatings or other surface treatments to enhance performance or protect against corrosion.

Overall, the manufacturing process for electric vehicle motors requires a combination of precision machining, assembly, and materials science expertise to produce high-performance and reliable motors.

3.8 Motor Thermal Management

Thermal management of the traction motors is extremely important for the efficient and safe operation of electric vehicles, particularly in tropical Indian conditions. Effective thermal management of the motor can improve the real-world range of electric vehicles, and avoid insulation losses of windings, and demagnetization of permanent magnets. It also helps to increase the rated power of the machine significantly without much increase in the manufacturing cost.

The electric vehicle range is dependent on temperature as the performance of the key components is impacted by their operating temperatures. Ambient temperature in India may reach about 40-45^{O}C during summer, which may affect the performance of the traction motors. The battery is the most impacted, but when the temperature goes beyond 100^{0} C, the performance of the motor and power electronics is also affected.

At higher temperatures, coil resistance increases, resulting in a decrease in motor torque and magnetic flux.

Thermal management strategy needs a holistic approach, as various components of the EV drivetrain are closely related in terms of their thermal management and associated performance. At very low temperatures, the useable capacity and power output of the lithium-ion battery are reduced, which in turn reduces the power capability of the traction motor. Similarly, degradation of the battery starts at 35^{o}C, which again may cause a decrease in the power capability of the traction motor. Safety and battery life are the major concerns at higher temperatures.

The thermal management system needs to be energy efficient. The thermal management system essentially needs to consider three different aspects:

Traction battery: The present state of the art is a lithium-ion battery. For these batteries, the chemical reactions become slow at temperatures below 0°C. On the other hand, the battery deteriorates exponentially above 30°C, and serious irreversible damage may occur at temperatures beyond 40°C. Considering the tropical climates of India, where the ambient temperature may be beyond 40°C during summer, it is a challenge to design a thermal management system that meets such conditions. Accordingly, there is a need for battery development suitable for tropical conditions, and this issue is covered under White Pape*r 1: Tropical EV Battery*. Battery cooling options include air-cooling, cooling with coolants and refrigerants, and direct cooling or secondary cooling. At higher ambient temperature, another option is to use a heat exchanger to transfer the low temperature of the evaporating refrigerant from the climate circuit to the battery cooling circuit.

Electric motor and power electronics: The two major options for cooling electric vehicle motors include air cooling and liquid cooling. Further, air cooling may be either natural or forced. Liquid cooling uses water and ethylene glycol. The water-ethylene glycol mixture is used in cooling jackets for indirect cooling. Hot spots in the internal parts are cooled directly with the help of liquid (viz., Oil spray over the end winding). Modern traction motors for electric vehicles have high speed and high power density, reduced diameter, and axial length. However, this is associated with higher heat generation, which may affect the motor's life unless appropriate cooling methods are adopted. Thermal management also increases motor efficiency and prevents demagnetization of the permanent magnets. Motor cooling helps to slow down insulation aging**.** Resistance increase in the conductors and delamination risks of stacked metal sheets. Whereas conventional lubricants used in automobiles are designed to optimize friction and fuel economy [22]. The development of a new type of fluid that can cool the motor efficiently and provide high-performance lubrication for the transmission is desirable.

Since the heat generation of the motors is due to losses, the priority is cost-effective ways of minimizing such losses. The different types of losses are (1) Rotor copper loss (Resistive), (2) Stator copper loss (Resistive), (3) Iron core loss, (4) Friction and windage losses, and (5) Stray losses.

Broadly, the thermal management systems for vehicles are (1) High-Temperature Loop for the engine, (2) Medium Temperature Loop for electric motor and power electronics, (3) Low-Temperature Loop for the batteries.

Among these, the first one is relevant only for vehicles with IC engines such as Hybrid Electric Vehicles (HEVs). For each type of cooling loop, a coolant fluid is circulated using an electric pump to cool the target devices or subsystems, and a radiator is used to release heat into the ambient air. Since in most cases the desired operating temperature of electric motor and power electronics are the same, a common cooling circuit may be utilized for both.

Options for coolant fluid include air, oil, water-ethylene glycol mixture and refrigerant. The electric motor has multiple heat paths with multiple materials and thermal interface. All these make the thermal management of electric vehicle motors complex and challenging.

The suitable cooling methods (or combination of them) depend on the power-train weight as well as the peak power of the motor. For heavy weight power-train with high peak power motor, the most complex combination of cooling methods is required. Development of motors with higher power density will lead to simpler cooling methods in such cases.

The thermal management system for the motor and electronics can be designed from the entire vehicle thermal management perspective and a suitable control system for series and parallel operation of various coolant loops depending on ambient conditions may also be designed. Accurate temperature measurements of critical components like stator winding and MOSFETs are key to have effective thermal management. Inferred method also helps to predict the component temperature. A strong derating strategy is another important method to realise operation with a higher reliability. Optimum thermal management system for electric vehicle will depend on various factors such as the ambient temperature, vehicle mission and performance, homologation requirement, safety and quality. The challenges are different for different categories of electric vehicles. Electric two-wheelers, which are expected to dominate the Indian EV market in near future, have stringent space, weight and cost constraints. Considering these, an initiative on optimum thermal management system for various categories of Indian electric vehicles and associated controller development is required.

3.9 Electric Motors: Key Points

- To meet the demand for compact, high speed motors with high torque and power density, PMBLDC and PMSM motors are most suitable option in the short term. Development of supply chain for PMSM motors is critical for widespread adoption of electric mobility in India.

- Development of low-cost non-rare earth motor technologies is important for long-term sustainability of the Indian electric vehicle ecosystem and options such as SRM, SynRM and PM assisted SynRM have emerged as serious contenders to PMSM.

- Alternative magnets that either do not use critical raw materials or use reduced amount of them is one research area that should be pursued.

- There are possibilities for innovation in motor architecture/ topology and design with multi-objective design optimization for various categories of electric vehicles.

- Initiatives towards improved thermal management appropriate for Indian conditions for BLDC and PMSM motors need to be taken up.

- A special emphasis should be in the development of competency in the various parts of the electric motor supply chain including the equipment, magnet manufacturing, motor design, control system design, and packaging and integration.

- Capability for precision manufacturing plays an important role towards development of high speed and efficient electric motors.

- Additive manufacturing can potentially help development of lightweight electric motors and their integration with the drive units. Additive manufacturing has facilitated lage scale production of axial and transverse flux motors which are torque dense compared to current industry standard radial flux motors. Additive manufacturing effectively uses soft magnetic composite (SMC) powders in manufacture of electric motors of improved efficiency and high specific torque to weight ratio.

- Packaging of motors with cooling, drive electronics, transmission bearing etc. into an integrated axle package which is resistant to dust, moisture, water, shock and vibration and compliant to EMI/EMC requirements is another area of importance. The design should also address issues of reliability, maintainability.

- On-line motor health monitoring systems and fault diagnosis systems based on sensed measurements and digital twins is an area of importance.

04

RECOMMENDATIONS

4.1 CoE for the Integration of Electric Vehicle Systems

Vehicle integration is a critical aspect of an EV Powertrain. The Motor Control and the PE controller must operate under a supervisory vehicle control system which works in continuous collaboration with BMS, the Transmission and the Brake Controllers in response to the driver inputs to achieve performance parameters such as energy efficiency, safety and drivability, battery life, electric range etc. The following are among the important issues to be focussed on.

Although a vehicle control system needs to be customised for a vehicle, a common standardized parameterised and modular architecture may be conceived for various power categories that may be used in 2/3/4 W, etc. It will help standardize the components used in various chargers, controllers, etc. In future, it will also help achieve economies of scale at component and child part levels, including semiconductor devices. Efforts must be made to promote such discussions in the industry forums.

There are various paradigms for efficient energy management for EVs and HEVs. The energy management system (EMS) must operate under various technical operating constraints imposed by the tier 1 suppliers for batteries, motors, electronics etc. Therefore, there is a need to tune the parameters of the EMS across models of vehicles which may use different subsystem ratings and specifications. Similarly, there arises need for tools to tune such controllers at the dealerships after maintenance events for the vehicle. In an advanced vehicle, such a tuning may be continuously tracking the vehicle system ageing and degradation and adapting the energy management over the life cycle. Development of such real-time supervisory software and lead to favourable ownership values and enhance adoption of EVs.

Monitoring vehicle performance based on data acquired from subsystems including that of its power train can provide important feedback to the user related to safety, capacity, remaining useful life, maintenance etc. and can be attractive features of the vehicle. Such data can also be collected from vehicles on the road easily by OEMs and fleet managers and analysed using a cloud computing system. to monitor individual vehicles. Such software and data applications is another area that should be focused on.

Development and application of simulation tools to study different power train configurations to meet functional requirements as well as vehicle dynamics under realistic use cases is an important requirement of OEMs. Such simulations must be done at various levels known as Model-in Loop (MIL), Software-in Loop (SIL), Processor-in Loop (PIL) and Hardware-in Loop (HIL). Moreover, such simulations need to integrated with Traffic and Drive Simulators. Development of these environments, standardising test cases for different vehicle types in a third aspect of focus.

A consortium may be initiated with Agencies like ARAI or ICAT, CDAC-T, National Laboratories like CECRI, CMERI, CEERI, Academic Institutions and OEM and component supplier Industries including start-ups and MSMEs, standard organisations like BIS. The CoE needs to work along with the CoE for Electric Vehicle Motors and CoE for Power

Electronic Converters to develop integrated technology to meet vehicle applications. This consortium should take up the development of standards and target specification of EV power trains and their component subsystems like Motors, Inverters etc.

The vehicle electronics shall meet the EMI standards so that the electromagnetic interference shall not disturb the performance of the vehicle electronics and other communication systems. EMC standards are to be evolved by a testing agency.

4.1.1 CoE on Integration of Electric Vehicle Systems: Short-Term Priorities (TRL 5-7)

The immediate focus needs to be on making the EV better performing in terms of key performance parameters such as energy efficiency, battery life and safety. The other need to be met is to enhance tools and competencies for technology development. The short-term priorities include:

1. Development of energy management systems of electric and hybrid electric vehicles. Real-time optimization of control of subsystem operating points to enhance drivetrain efficiency, drivability, optimization of battery performance and safety etc.
2. Development of integrated thermal management system for EVs encompassing battery, motor and passenger cabin.
3. Establishment and use of simulation environment with a MIL/SIL/PIL/HIL feature to support design and evaluation of EV powertrains under realistic use cases.
4. Development of Digital Twin based applications comprising physical models, data analytics, artificial intelligence, and machine learning to support the production, operation, and maintenance of electric vehicles. These may be integrated with smart displays, diagnostic tools and wireless services for the user.
5. Development of ADAS features for enhanced safety, stability, energy efficiency, drive comfort etc. for specific drive use cases such as traffic jams or hills, particularly for smaller vehicles with cheap sensors and processors.
6. Development of connected EVs for collection of data related to electric vehicle use, performance, charging etc. for purposes of analysis of region-wise real-life drive cycles, monitoring of individual vehicle performance etc. and for even governance and societal reasons, using wireless communication and cloud computing
7. Setting up of Test and Certification facilities across India
8. Platform independent controller firmware

4.1.2 CoE on Integration of Electric Vehicle Systems: Medium-Term Priorities (TRL 3-5)

The intermediate focus needs to be on innovating new powertrain architectures for the EV and the HEVs., in terms of energy transformations, in terms of information processing, in terms of product features, suited to specific Indian market segments and with positive global impacts on environment, sustainability and the economy. The medium term priorities include:

1. Development of prototype hybrid electric vehicles with Fuel Cells, Hydrogen Combusting Engines (HCE), CNG etc. along with batteries and motors
2. Development of architecture, tools and standards for Software Defined Vehicles (SDVs) to create, manage, upgrade the considerably increasing volume and complexity of software to provide the best customer value over the vehicle lifecycle.
3. Vehicle interfaces for charging infrastructure (e.g. Wireless and Fast chargers)
4. Vehicle Integrated Solar Photovoltaic Systems
5. Security against cyberattacks as well as for maintenance of privacy of vehicle data.
6. Configurable powertrains for optimal performance under specified use cases. These may be applicable for customers with specific use cases and also for applications of BAAS or battery swapping models.
7. Development of tools and apps for EV stakeholders for support services related to charging, maintenance, emergency, warranty and insurance etc.

4.1.3 CoE on Integration of Electric Vehicle Systems: Long-Term Priorities (TRL 1-3)

The long-term focus needs to be on inventing futuristic powertrain architectures for the EV and the HEVs., in terms of use of sustainable and futuristic energy sources, new paradigms of mobility, related engineering design, prototyping and information processing, suited to Indian conditions and with positive global impacts on environment, sustainability and the economy. The long-term priorities include:

1. Use of Small Modular Reactors for large vehicles
2. Magnetic Levitation for applications like Trams and Metros
3. New and futuristic concepts in electric mobility such as modular electric vehicles
4. Development of propulsion and energy management for vehicles with various energy sources as well as energy storage systems.
5. Autonomous vehicles
6. Multi-mode vehicles for agriculture and defence applications.

4.2 CoE on Power Electronics

Development of indigenous PE switches with integrated gate drive, protection and cooling is one of the top R&D priorities. This area overlaps with the National Semiconductor Mission. It may be emphasised that the development of indigenous power switches may be made a priority target for the Semiconductor Mission in view of the large indigenous market for these for EVs.

Conventionally, IGBTs are used as switching devices. Inverters built around the modern Wide Bandgap Devices (WBD), such as SiC and GaN switching devices are good candidates for EVs in place of size reduction due to high frequency operations, high efficiency and high reliability in high temperature operation.

Developing hardware and software for WBD-based inverter control is therefore needs to be a focus. Typically, controllers are built around a standard RISC-based microcontroller or digital signal processor. Developing VHDL-based software for controllers that can be ported to FPGA-based hardware boards is a prospective alternative. Suitable safety, thermal management and EMI/EMC issues shall be ensured through packaging technology.

While considering multiphase motors, inverter topologies suitable for multiphase and multi-stack motors need to be developed.

The recent developments in multiport converters have features to integrate multiple sources like Solar PV, battery, etc. to realize a stable DC auxiliary power source.

Again, similar to the case of EV Motors, a consortium may be created with the participation of National Laboratories., Academic Institutes and Industry. The consortium also needs to include participation of lab(s) under DSIR who can contribute to packaging technology. The CoE on PE needs to be coordinated with the CoE for EV Motors as well as for EV Integration, Batteries and Charging Infrastructure.

4.2.1 CoE on Power Electronics: Short-Term Priorities (TRL 5-7)

In the short term, major focus will be achieving economy of scale, functional integration and modularity of inverter/converters for their integration in indigenous EV power trains leading to self-reliance in PE design and manufacturing for EVs. This phase may be aimed at creating competencies, resources and echo-system for PE products for EVs in India by 2030.

1. Automotive grade inverter/ converter manufacturing with conventional switches, as well as WBD-based switches including suitable passive components for automotive inverter/ converter circuits like electrolytic capacitors, film capacitors, power inductors, transformers, chokes, PCB etc.
2. Development of PE and controllers for EV chargers of Levels 1,2 and 3 and their integration with PV and other RE systems and with BESS.

3. Inverter topologies suitable for multiphase/multi-stack motors
4. Sensing/ sensor less methods for inverter control
5. Developing hardware and software for WBD-based inverter control including VHDL-based software for controllers that can be ported to FPGA-based hardware boards.
6. Inverter/ converter built around SiC for the operational voltage is more than 400V DC or 200V AC
7. Exploratory research activities in PE technology and topology

4.2.2 CoE on Power Electronics: Medium-Term Priorities (TRL 3-5)

In this phase the attempt shall be to advance on the technologies developed to achieve a higher level of lifecycle performance and cost based on scalable design and development of more integrated components and systems.

1. Development of advanced PE configurations, including:
    a. Inverters for enabling high-frequency, high-speed and high power operation of the motors
    b. Functionally integrated inverter/ converters for higher power density, efficiency and reduced weight
    c. Bidirectional converters for Vehicle-to-Grid functionality
    d. Multi-port converters for EV applications interfacing hybrid batteries, super-capacitors, PV arrays, fuel cells etc.
    e. Development of a modular converter architecture and digital control of EV PE hardware that can be deployed/upgraded in different vehicle platforms
    f. Active charge balancing architecture for vehicle batteries
2. Development of semiconductor technologies for WBD such as SiC and GaN. This needs to be done in synergy and collaboration with India Semiconductor Mission
3. Development of appropriate packaging, thermal management system and structural integration against vibration and shock for PE hardware for achieving high level integration with motors, batteries, transmission and brake for e-axles.
4. Integrated inverter condition monitoring, diagnostics with adaptive and fault tolerant control. Automated BIT methods and diagnostics for PE Boards

4.2.3 CoE on Power Electronics: Long Term Priorities (TRL 1-3)

These include futuristic technologies which may help produce the next generation of EVs and also impact other sectors such as Aviation and Energy. Also these would be aimed to meet the strict environmental and sustainability demands. Examples may include:

1. 3-D printed drives with power electronics embedded on the stator or rotor
2. Advanced materials and manufacturing of converters/ power modules to maximize lifecycle performance and cost
3. Integration of the inverter components including component packaging, sensors, gate driver, protection and thermal management, system integration, isolation, EMI/EMC and fabrication techniques.
4. High frequency inverters for Dynamic Wireless Power Transfer (DWPT) Systems
5. Development of device as well as converter level technologies for ultra-wide bandgap devices (UBD)
6. Automated test, diagnostics, prognostics and overall integrated health management.

4.3 CoE on Traction Motors

EV motors are required to be compact due to space restrictions, high torque density, leading to high slot fill factors and low airgap, due to drive requirements, subjected to wide thermal variation due to variations in load and ambient conditions as well as vibration and shock due to road conditions. This demands advanced manufacturing processes.

Even though PMSM motors are highly efficient and torque-dense, in terms of low cost, simpler manufacturing, low maintenance, magnet-less motors such as induction motors and switched reluctance machines have advantages. Considering improved efficiency, BLDC machines and SynRMs are also promising.

A major challenge lies in finding suitable materials and associated manufacturing processes for low iron and copper loss in the stator and the rotor. Firstly, therefore, advanced low-resistance and low reluctance high quality affordable magnetic material such as nanomaterials, is a high priority research area for EV motors. Similarly, material for conductors and insulators appropriate for voltage and current levels with sustainability features linked to extraction and recycling are also important.

Secondly, high quality and productivity manufacturing processes and machines for winding, assembly, to produce and assemble precise and thin laminations are to be developed. Compact speed, position and current sensing is also a requirement. Design and manufacture of rigid and high speed shafts and bearings, reliable methods of joining metal, thermal management components such as circulating water cooling plates etc. need to be supported.

Robust performance under degradation and failure tolerance are highly desirable for EVs. Technologies such as motor digital twins, adaptive, multiphase machines and drives and need to be developed for e-mobility applications beyond conventional three-phase machines.

For all the above methods and tools for multiphysics integrated design and simulation of motors, inverters and drives under realistic road, load and drive conditions are needed.

To support R&D to address these issues a consortium may be created to constitute this CoE. The CoE may be in consortium mode with the participation of researchers from academia, R&D and industry, including international entities, who are actively involved in motor technology research, for developing new motors for EV systems. An academic Institution like IIT/IISc or a CSIR laboratory like CMERI or CEERI can lead the activity with a Nodal Centre reporting directly to a National Steering Committee.

The consortium to drive focussed and directed high TRL research in the different identified motor technologies with specific deliverables for the EV industry. It should also undertake low TRL fundamental research to develop advanced technologies like magnetic bearings for high speed motors suitable for the Indian environment, sustainability factors and markets. It will manage the whole national motor technology development activities and monitor it for timely progress. Naturally, it needs to work along with the CoE for Integration of Electric Vehicle Systems.

4.3.1 Short Term Priorities: CoE on Traction Motors (TRL 6-7)

Development of competency in manufacturing of traction motors will be the short-term priority. Works need to be carried out on various manufacturing process technologies and equipment. A few pilot manufacturing facilities/ test-beds need to be developed that will support the developmental activities of the academic/ R&D institutions as well as industry, particularly start-ups and MSMEs. Such pilot facility/ test bed will also have facilities suitable for carrying out research on emerging manufacturing techniques for electric motors and their components.

The R&D activities shall have a major thrust on development of alternative motor technologies with comparable efficiency, power density and torque density as REPM, along with capability of higher speed operation. Various topologies of Switched Reluctance Motor and Synchronous Reluctance Motor will be the main focus. Typical target specifications for various classes of vehicle applications shall be obtained from industry.

Short-term activities on EV Motor will include

1. Simulation and design, optimization of design parameters and topology for higher specific power and torque density motors of various categories for various applications. Also design of e-axles of integrated motors, drives, cooling and transmission.
2. Health monitoring using Digital Twins for maintenance and fault tolerance.
3. Development of controller. Focus will be on development of advanced controllers to enhance lifecycle performance, efficiency, size and cost of EV drives for various motors.
4. Prototype development for target vehicle applications with OEMs and Integration with the vehicles
5. Exploratory research activities in motor technology and materials

While the major thrust will be on developing alternative technologies, the development of REE-PM-based PMSM also needs to be pursued, with a special focus on developing a supply chain based on REEs available in India.

4.3.2 CoE on Traction Motors: Medium Term Priorities (TRL 4-6)

The medium term priorities (TRL 4-6) are targeted at higher level of value addition and self-reliance in the motor value chain and should include:

1. Development of indigenous manufacturing technologies for motor sub-components, processes such and winding, lamination, casting, joining and raw materials such as electrical steel, conductor alloys etc.
2. Processing technology for rare-earth materials for magnet production
3. Development of specifications for magnets suitable for various categories of electric vehicles under Indian conditions; Development of magnets with rare earth material available in India.
4. Manufacturing for high quality and high reliability, and maintainability
5. IVHM and adaptive fault tolerant drives for various motor types for life-cycle performance
6. Thermal management of EV Motors.
7. Axial flux and multi-stack motors
8. Development and manufacturing of e-axles of integrated motors, drives, cooling and transmission.

4.3.3 Long Term Priorities: CoE on Traction Motors (TRL1-3)

These activities will be directed towards achieving the long-term sustainability targets towards efficient, compact, cost-effective electric motors for various categories of vehicles under Indian conditions.

1. New materials such as insulators, thermal fluids, coatings etc. that can contribute towards higher efficiency, lower cost, and higher power and torque density
2. Manufacture of high power and high speed motors with improved power density, torque density and efficiency
3. Development of alternative permanent magnets with characteristics suitable for EV motors
4. Advanced technologies such as emerging motor topologies, such as Transverse Flux Machines, multi-winding and high voltage-high power motors, inverters and drives.
5. Development of a "Design-for-Recycle" guideline for magnets across its value chain identification of relevant technologies. Development of technologies for recycling of magnets.

4.4 Conclusions

The Government of India has been proactively patronizing electric mobility in the country through various interventions such as demand incentives, infrastructure support, tax reduction, creation of standards, pilot fleet demonstration, test facilities and technology development. However, for long term competitiveness of electric vehicles, a roadmap for reducing the dependence on subsidies in future need to be in place, and to achieve this target technology plays a crucial role. Recently the Government of India has announced the PM E-DRIVE scheme that offers subsidies to electric 2/3 wheelers and buses. The amount of subsidy is to reduce by half after one year. Technology development can ensure creation of a self-sufficient domestic EV value-chain and overcoming the hindrances to the widespread adoption of electric vehicles in the country. This document has attempted to delineate a roadmap for overcoming the hindrances to electric mobility in the country through technological interventions in the area of Power Electronics, Machines and Drives.

Three Centres of Excellence are proposed each having short term (TRL 6 to 7), medium term (TRL 4 to 6) and long term (TRL 1 to 3) objectives. The CoE on Integration of Electric Vehicle Systems will focus on enhancing the performance parameters of electric vehicles (e.g., energy efficiency, battery life and safety) along with the tools and competencies for technology development. Innovating new powertrain architectures for the EV and the HEVs will be the intermediate focus. The long-term focus needs to be on inventing original new powertrain architectures for the EV and the HEVs.

The short-term objective of the CoE on Power Electronics will be achieving economy of scale, functional integration and modularity of inverter/converters for their integration in indigenous EV power trains leading to self-reliance in PE design and manufacturing for EVs. This phase may be aimed at creating competencies, resources and echo-system for PE products for EVs in India by 2030. In the medium term, the attempt shall be to advance on the technologies developed to achieve a higher level of lifecycle performance and cost based on scalable design and development of more integrated components and systems. The long-term priorities include futuristic technologies which may help produce the next generation of EVs and also impact other sectors such as Aviation and Energy. Also these would be aimed to meet the strict environmental and sustainability demands.

Development of competency in manufacturing of traction motors will be the short-term priority for CoE on Traction Motors. This will include developing a few pilot manufacturing facilities/ test-beds to support the developmental activities of the academic/ R&D institutions as well as industry, particularly start-ups and MSMEs. Development of alternative motor technologies will be the main focus of R&D. The medium-term priorities will target higher level of value addition and self-reliance in the motor value chain. Long term activities will be directed towards achieving the long-term sustainability targets towards efficient, compact, cost-effective electric motors for various categories of vehicles under Indian conditions.

With electric mobility having a major role in India's journey towards Net Zero Emission, concerted actions towards development of the key technologies bringing together various stakeholders are desirable. It is expected that this document will be able to catalyse such concerted actions. DST shall take a lead role to network with stakeholders and constitute the CoEs and manage them with the help of a National Level Planning and Steering Committee to expedite the activity through continuous coordination, monitoring and review.

GLOSSARY

ABS: Anti-lock Braking System

AC/DC: Alternating Current to Direct Current (converter)

ADAS: Advanced Driver Assistance Systems

AFM: Axial Flux Motor

AlNiCo: Aluminium-Nickel-Cobalt

APM: Auxiliary Power Module

ARAI: Automotive Research Association of India

ARPA-E: Advanced Research Projects Agency-Energy

ASR: Anti-Slip Regulation

BAAS: Battery as a Service

BEV: Battery Electric Vehicle

BJT: Bipolar Junction Transistor

BLDC: Brushless Direct Current

BMS: Battery Management System

CAN: Controller Area Network

CeCo: Cerium Cobalt

CECRI: Central Electrochemical Research Institute

CEERI: Central Electronics Engineering Research Institute

CMERI: Central Mechanical Engineering Research Institute

CNG: Compressed Natural Gas

CoE: Center of Excellence

CPSR: Constant Power Speed Range

CSI: Current Source Inverter

CLLC: Capacitor-Inductor-Inductor-Capacitor (Resonant Tank)

DC: Direct Current

DC/DC: Direct Current to Direct Current (converter)

D/L: Diameter to Length ratio

DSIR: Department of Scientific and Industrial Research

DWPT: Dynamic Wireless Power Transfer

dv/dt: Rate of Change of Voltage with Respect to Time

EESM: Electrically Excited Synchronous Motor

EFT: Electrical Fast Transients

EMI: Electromagnetic Interference

EMI/EMC: Electromagnetic Interference/Electromagnetic Compatibility

EMC: Electromagnetic Compatibility

EMS: Energy Management System

ESP: Electronic Stability Program

EV: Electric Vehicle

FPGA: Field Programmable Gate Array

FIBC: Floating Interleaved Boost Converter

GaN: Gallium Nitride

HESM: Hybrid Excited Synchronous Motor

HEV: Hybrid Electric Vehicle

HIL: Hardware-in-Loop

HIPOT: High Potential (Test)

HV: High Voltage

HVIL: High-Voltage Interlock Loop

HVAC: Heating, Ventilation, and Air Conditioning

IC: Internal Combustion (Engine)

ICAT: International Centre for Automotive Technology

IGBT: Insulated Gate Bipolar Transistor

IM: Induction Motor

IP: Ingress Protection

IVHM: Integrated Vehicle Health Management

LV: Low Voltage

MIL: Model-in-Loop

MSME: Micro, Small, and Medium Enterprises

MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

MCU: Microcontroller Unit

NdFeB: Neodymium Iron Boron

NVH: Noise, Vibration, Harshness

OBC: On-Board Charger

OEM: Original Equipment Manufacturer

PAI: Polyamide-Imide

PE: Power Electronics

PEMD: Power Electronics, Machines, and Drives

PFC: Power Factor Correction

PHEV: Plug-in Hybrid Electric Vehicle

PHY: Physical Layer

PMASynRM: Permanent Magnet Assisted Synchronous Reluctance Motor

PMBLDC: Permanent Magnet Brushless DC

PMSM: Permanent Magnet Synchronous Motor

PDU: Power Distribution Unit

PWM: Pulse Width Modulation

RE: Rare Earth

REE: Rare Earth Element

REPM: Rare-Earth Permanent Magnet

REPMM: Rare Earth Permanent Magnet Motor

RF: Radio Frequency

RISC: Reduced Instruction Set Computer

RθJC: Junction-to-Case Thermal Resistance

R&D: Research and Development

SDV: Software Defined Vehicle

Si: Silicon
SiC: Silicon Carbide
SIL: Software-in-Loop
SMC: Soft Magnetic Composite
SMPS: Switched-Mode Power Supply
SOC: State of Charge
SOH: State of Health
SRM: Switched Reluctance Motor
SynRM: Synchronous Reluctance Motor
TFM: Transverse Flux Machine
THD: Total Harmonic Distortion
TJ(max): Maximum Junction Temperature
TNPC: T-type Neutral Point Clamped
TO-220: A Type of Transistor Package
TRL: Technology Readiness Level
UBD: Ultra-Wide Bandgap Devices
UNECE: United Nations Economic Commission for Europe
UIS: Unclamped Inductive Switching
UPS: Uninterruptible Power Supply
US-DoE: United States Department of Energy
V2G: Vehicle to Grid
V2H: Vehicle to Home
VCU: Vehicle Control Unit
VHDL: VHSIC Hardware Description Language
VSI: Voltage Source Inverter
WBD: Wide Bandgap Devices
WBG: Wide Band Gap
ZCS: Zero Current Switching
ZSI: Z Source Inverter
ZVS: Zero Voltage Switching

LIST OF AUTHORS AND CONTRIBUTORS

R&D Roadmap Coordinator: Mr. Suresh Babu Muttana, Scientist E, DST

ADVISORY COMMITTEE	
1. Prof. B G Fernandes, Indian Institute of Technology (IIT), Bombay	Chairman
2. Dr. Anita Gupta, Head, Climate, Energy and Sustainable Technology (CEST) Division, Department of Science & Technology (DST), GoI	Co-chair
3. Prof. Siddhartha Mukhopadhyay, IIT Kharagpur	Technical Advisors
4. Mr. Sajid Mubashir (former) Scientist G, Department of Science & Technology, GoI	
5. Dr. Raghunathan, Professor of Practice, IIT Madras; Former Technical Fellow-General Motors - Battery Cell Technology	
6. Mr. Suuhas Tenddulkar, Program Director, Environmental Resource Foundation (ERF)	
7. Ms. Veena Koodli, Technical Expert EV charging, Robert Bosch, Bangalore	
8. Dr. Z V Lakaparampil (former) Sr. Director, C-DAC, Thiruvananthapuram, and Director, AJCE	
9. Dr. Kiran Deshmukh, Executive Director, Sona COMSTAR	
10. Prof. Vijay Mohanan Pillai, IISER, Tirupati	
11. Dr. A Ramesha, Director, CECRI, Karaikudi	
12. Mr. Suresh Babu Muttana, Scientist E, DST	Member Secretary

Contributors of R&D Roadmap

POWER ELECTRONICS, MACHINES AND DRIVES (PEMD)	
Authors	Mr. Arghya Sardar, TIFAC Dr. Parveen Kumar, World Resources Institute India Dr. Renji Chacko, CDAC Thiruvananthapuram Dr. Chandra Sekhar Nalamati, LTTS Dr. Prashant Upadhyay, LTTS Dr. Amit Kumar Gupta, LTTS Dr. Gourav Kumar Mishra, LTTS Dr. Rohan Malhotra, DST Science Policy Group Mr. Suresh Babu Muttana, DST Dr. Perminder Jit Kaur, DST-Centre for Policy Research, IISc, Bangalore
Contributors	Mr. Sajid Mubashir (formerly), DST Dr. A.K. Jindal, Tata Auto components (TACO) Dr. R N Patra (formerly), IREL Dr. Kiran Deshmukh, Sona Comstar Dr. Karun Malhotra (formerly), Murata Group Dr. K Balasubramanian, NFTDC, Hyderabad Dr. Raghavan Gopalan, ARCI, Hyderabad Mr. Ruchir Shukla, Shakti Foundation Dr. Z V Lakaparampil (former) Sr. Director, C-DAC, Thiruvananthapuram, and Director, AJCE Mr. Tejas Khsatriya, KPIT Mr. Vinay Kulkarni, KPIT Mr. Puneet Jain, Grinntech Motors & Services Pvt. Ltd. Mr. M Vasu, LTTS Mr. Srinivas Kudligi, Aditya Avartan Technologies Pvt. Ltd. Mr. IV Rao, TERI Dr. Anurag Verma, DST & TERI

REFERENCES

[1] J. Reimers, L. Dorn-Gomba, C. Mark and A. Emadi, "Automotive traction inverters: Current status and future trends," *IEEE Transactions on Vehicular4 Technology,* vol. 68, no. 4, pp. 3337-3350, April 2019.

[2] U.S. Drive, "Electrical and Electronics Team Technical Roadmap," U.S. Drive, October 2017.

[3] Powertrain International, "Equipmake launches silicon carbide inverter (SiC) for electric vehicles," Powertrain International, 10 March 2022. [Online]. Available: https://www.powertraininternationalweb.com/components/equipmake-silicon-carbide-inverter/. [Accessed 01 September 2024].

[4] Equipmake, "HPI-800," Equipmake, [Online]. Available: https://equipmake.co.uk/products/hpi-800/. [Accessed 01 September 2024].

[5] Engineering Research Centers, "Electric Vehicles Inverter Developed with Twice the Efficiency, Smaller Size than Commercial Systems," Engineering Research Centers, [Online]. Available: https://erc-assoc.org/content/electric-vehicles-inverter-developed-twice-efficiency-smaller-size-commercial-systems. [Accessed 01 September 2024].

[6] S. Hanley, "New SiC Inverter For Electric Cars Saves Money," Clean Technica, [Online]. Available: https://cleantechnica.com/2022/03/07/new-sic-inverter-for-electric-cars-saves-money/. [Accessed 06 September 2024].

[7] ShinDengen, [Online]. Available: www.shindengen.com .

[8] K. Specht, M. Gall and G. Scheidhammer, "From 400 to 800 V - Effects on the High-Voltage On-board Eletrical System," *ATZ Electronics Worldwide ,* pp. 42-45, 2019.

[9] Z. J. Shen and I. Omura, "Power Semiconductor Devices for Hybrid, Electric and Fuel Cell Vehicles," *Proceedings of the IEEE,* vol. 95, no. 4, pp. 778-789, 2007.

[10] Valeo, "Charger Inverter for Electric Vehicles," Valeo, [Online]. Available: https://www.valeo.com/en/charger-inverter-for-electric-vehicles/. [Accessed 05 09 2024].

[11] O. Bernatchez, "Bi-directional charger inverter : Combining multiple functionalities into one box," TM4, [Online]. Available: https://www.danatm4.com/bidirectional-charger-inverter-combining-multiple-functionalities-one-box/. [Accessed 05 September 2024].

[12] ARPA-E, "Iron-Nickel-Based Supermagnets," [Online]. Available: https://arpa-e.energy.gov/technologies/projects/iron-nickel-based-supermagnets#:~:text=This%20iron%2Dnickel%20crystal%20structure,by%20the%20Northeastern%20University%20team.. [Accessed 10 December 2023].

[13] W. Soong and T. Miller, "Field-weakening performance of brushless synchronous AC motor drives," *IEE Proceedings - Electric Power Applications,* vol. 141, no. 6, pp. 331-340, 1994.

[14] M. A. Willard, "Stronger, Lighter, and More Energy Efficient: Challenges of Magnetic Material Development for Vehicle Electrification," U.S. Naval Research Laboratory, Washington, DC.

[15] L. Schmid-Schmidsfelden, “Are you interested in Miba technology for axial flux motors?,” Miba AG, [Online]. Available: https://www.miba.com/en/emobility/axial-flux-motor. [Accessed 2024 July 2024].

[16] “Yasa Motors,” [Online]. Available: https://yasa.com/technology/.

[17] T. Drabek, P. Kapustka, T. Lerch and J. S. ´nski, “A Novel Approach to Transverse Flux Machine Construction,” *Energies,* vol. 14, no. 7690, 2021.

[18] Z. Zhu and S. Cai, “Hybrid Excited Permanent Magnet Machines for Electric and Hybrid Electric Vehicles,” *CES Transactions on Electrical Machines and Systems,* vol. 3, no. 3, pp. 233-247, September 2019.

[19] C. Shukang, L. Cuiping, C. Feng and G. Hailong, “Research on Induction Motor for Mini Electric Vehicles,” *Energy Procedia,* vol. 17, pp. 249-257, 2012.

[20] G3SoilWorks, [Online]. Available: www.geologyengineers.com.

[21] Motor Design Limited, “Maximising E-Machine Efficiency with Hairpin Windings: Whitepaper,” 2021. [Online]. Available: https://www.motor-design.com/wp-content/uploads/Maximising-E-Machine-Efficiency-with-Hairpin-Windings-White-Paper.pdf. [Accessed 22 December 2022].

[22] N. Champagne, “Electric Mobility: A New Era for Thermal Fluids,” *Lube-Tech,* pp. 26-32, April 2022.

[23] Advanced Propulsion Centre UK; Automotive Council UK, “Power Electronics Roadmap 2020,” 2020.

[24] Advanced Propulsion Centre UK, “Power Electronics, Industry Challenges 2020-2035+,” May 2021.

[25] Sanford Magnets, “Advantages and Applications of Permanent Magnet Synchronous Motor,” [Online]. Available: https://www.stanfordmagnets.com/advantages-and-applications-of-permanent-magnet-synchronous-motor.html. [Accessed 29 July 2024].

[26] H. J. Kim and S. Kim, “Rare Earth Dispute and Trend in Development of NdFeB Anisotropic Bonded Magnets,” *Journal of the Korean Magnetic Society,* vol. 22, no. 3, June 2012.

[27] H. M. Soliman, “Improve the Performance Characteristics of the IPMSM Under the Effect of the Varying Loads,” *IET Electric Power Applications,* vol. 13, no. 12, pp. 1935-1945, 2019.

[28] Lamnow Laminations, “Is Switched Reluctance Motor the Future of Electric Vehicles?,” Lamnow Laminations, 8 March 2024. [Online]. Available: https://lamnow.com/is-switched-reluctance-motor-the-future-of-electric-vehicles/. [Accessed 31 July 2024].

[29] Wikipedia, “Induction Motor,” Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Induction_motor. [Accessed 31 July 2024].

विज्ञान और प्रौद्योगिकी विभाग
DEPARTMENT OF
SCIENCE AND TECHNOLOGY

सत्यमेव जयते

Climate, Energy and Sustainable Technology (CEST) Division
Department of Science & Technology (DST)
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