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Research Article

Technology Challenges and Trends of Electric Motor and Drive in Electric Vehicle

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Abstract: Electric traction drive systems must demonstrate advanced capabilities, such as improved fuel efficiency measured in miles per gallon of gasoline-equivalent (MPGe), extended range, and rapid charging options to achieve wider acceptance. This increased electrification and evolving mobility landscape have generated a demand for electric traction drive systems with higher power output and greater efficiency, resulting in better fuel economy per battery charge. To accelerate the widespread adoption of electrified transportation, the US Department of Energy (DOE) has collaborated with the automotive industry to establish technical targets for light-duty electric vehicles to be achieved by 2025. Deployment of publicly available EV charging points increased by close to 40% in 2021, although in 2020 the growth rate was higher at 45%. Nevertheless, 500 000 public charging points were installed in 2021, which is more than the total stock of chargers available in 2017. The rate of fast charger installations increased slightly in 2021 (up 48%) compared with 2020 (up 43%), while growth in slow charger installations slackened (33% in 2021, compared with 46% in 2020). This article investigates the current trends in electric drive technology for both hybrid electric and fully electric passenger vehicles. It evaluates commercially available solutions concerning materials, designs for electric machines and inverters, maximum speed, power density, and component cooling, as well as performance metrics. Furthermore, the article highlights upcoming materials and technologies for power electronics and electric motors, as well as the associated challenges and opportunities for achieving even more ambitious designs to meet the demands of the next generation of electric vehicles.

Keywords: Electrical Vehicles; Electric Machines and Drives; Traction Inverter

1. Introduction

Electric vehicles (EVs) are the critical technology for decarbonizing road transportation, which accounts for 16% of global emissions. EV sales have increased exponentially in recent years, owing to the improved range, wider model availability, and improved performance. Passenger EVs are becoming increasingly popular; we estimate that 13% of new cars sold in 2022 will be electric; if the growth seen in the last two years continues, CO2 emissions from cars can be reduced to meet the Net Zero Emissions by 2050 Scenario [1,2]. Electric vehicles, despite this, are not yet a worldwide phenomenon. Due to higher purchase costs and a lack of charging infrastructure availability, sales in developing and emerging countries have been slow. Moreover, EV sales reached a record high in 2021, despite supply chain bottlenecks and the ongoing Covid-19 pandemic. Compared with 2020, sales nearly doubled to 6.6 million (a sales share of nearly 9%), bringing the total number of EVs on the road to 16.5 million. The sales share of EVs increased by 4 percentage points in 2021. The Net Zero Emissions by 2050 Scenario sees an EV fleet of over 300 million in 2030 and electric cars accounting for 60% of new EV sales. Getting on track with the Net Zero Scenario requires their sales share to increase by less than 6% percentage points per year [2].

Energy density is key to ensuring that BEVs have sufficient range. The energy density of batteries for EVs has been rising over the past year, and now some of the highest performing battery cells can reach energy densities of over 300 Wh/kg, up from around 100-150 Wh/kg a decade ago – meaning that with the same mass, electric cars can now travel twice as far. This progress has been made thanks to continuous improvement in battery chemistry and cell design. Key examples of this include Tesla's upcoming 4680 cells and LG Energy Solution's Ultium cells. The global sales of EVs, comprising both battery EVs (BEVs) and plug-in hybrid EVs (PHEVs), exceeded five million units in 2019. Of the total sales, BEVs were found to have a higher share than PHEVs. The rate of adoption of EVs has shown a steady increase, with one million BEVs sold within a short span of six months, while the first million BEVs took five years to achieve. In this context, the urgent need to address environmental challenges and energy issues has led to an increased societal demand for vehicles that are clean, efficient, and sustainable for urban transportation. In response, both conventional original equipment manufacturers and newer generation manufacturers are offering a range of models with different features and varying ranges [3-8].

This significant progress in vehicle electrification has been accompanied by a profound transformation in society's perception of transportation, with autonomous driving and mobility as a service emerging as new paradigms that have created opportunities for greater freedom of movement. The advancements in electrification and changing landscape of mobility have resulted in a growing requirement for electric traction drive systems that deliver greater power and efficiency, leading to improved fuel economy per battery charge. The recent emergence of wide-bandgap (WBG) semiconductor-based drives, which offer high-frequency and high-temperature operation capabilities, has provided a critical impetus for enhancing the operating speed of traction machines. Furthermore, the latest developments in winding, lamination, and permanent magnet materials have enabled the electric motor design to push the boundaries for maximum speed and power/torque density through innovative design strategies.

In light of these findings, this article follows this organizational structure: **Section 2** illustrates Emerging developments in inverter design. **Section 3** highlights Emerging developments in the design of electric machines for high-speed applications. **Section 4** demonstrates the Traction inverter drive. **Section 5** discusses the conclusion of this paper. **Section 6** demonstrates the impact of WBG devices on motor insulation. Finally, **Section 7** discusses the conclusion of this article.

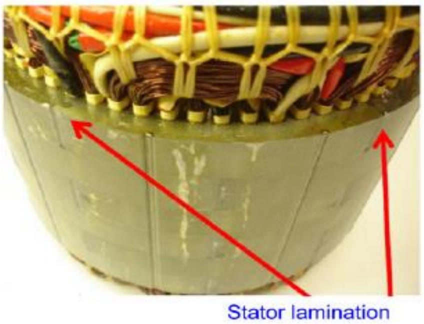
2. Emerging developments in inverter design

In battery electric vehicles/hybrid electric vehicles, the 3-phase voltage source inverter (VSI) topology is the prevalent choice for the traction inverters due to its simplicity in control requirements, low cost, and high efficiency. The primary components of the inverter drive are power devices and direct-current (DC)-link capacitors. Among these components, power devices are the most expensive, amounting to approximately 50% of the total drive cost. The EV industry has been utilizing Si-IGBT (insulated-gate bipolar transistor) as the primary power device in traction inverters for BEVs/HEVs since the debut of the first modern-day EV, EV1, in 1996, due to its favourable cost, decent efficiency, and good short circuit capability of around 10 μs. However, the latest advances in wide-bandgap (WBG) devices, particularly SiC and GaN devices, are expected to offer substantial power density and efficiency improvements in traction inverter drives [9-12]. To reduce the undesirable effects of the pulse-width modulated (PWM) operation of the inverter stage, a large DC-link capacitor (Cdc) is employed to minimize the ripple current and voltage. In automotive traction inverters, large polypropylene film capacitors are utilized due to their suitability for the working voltage (1.2 to 1.5 times the DC-link nominal voltage), root mean square (RMS) current, operating temperature, lifetime, parasitic inductance, and resistance. The inverter power devices, shielded alternating-current (AC) cables, and motor all exhibit significant parasitic capacitances to the ground, which is the vehicle chassis. The high rate of change of voltage concerning time, known as dv/dt, resulting from each pulse-width modulation (PWM) switching operation at the alternating current (AC) inverter terminals induces common mode (CM) pulses to the ground, leading to significant level of electromagnetic interference (EMI).

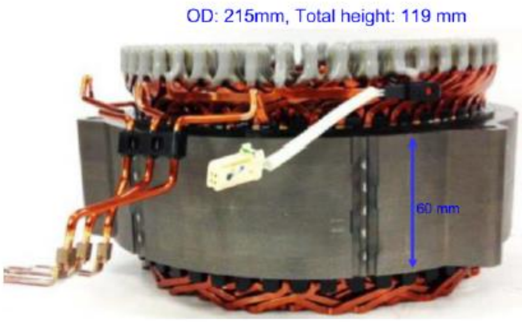
3. Emerging developments in the design of electric machines for high-speed applications

In electric and hybrid vehicles, the propulsion electric motor must possess several desirable features such as high starting torque to meet acceleration demands, high power density to minimize size and high efficiency to extend battery range. The motor drive system must also have a broad constant power speed range (CPSR) to support a single-gear transmission and thus, enhance the transmission power density and simplify its control. However, the wider CPSR necessitates a trade-off in the power density of the electric motor. Moreover, a broader CPSR results in an increase in the power requirements of the motor drive system. In the context of electric vehicles and hybrid electric vehicles, the drive unit for the electric motor should possess flexible control, high reliability, fault tolerance, and low acoustic noise. The two primary types of machines utilized in recent electric and hybrid electric vehicles are AC induction machines and interior permanent magnet (IPM) machines. The IPM synchronous motor (IPMSM) is preferred for traction electric machines due to its unmatched power/torque density and efficiency, making it a suitable choice to fulfil the rigorous requirements of an electric traction drivetrain [13-16].

Each of the rotor designs for interior permanent magnet (IPM) machines used in traction applications has its own merits and demerits. Typically, the double V-shape rotor provides the highest torque density and efficiency, but it suffers from elevated magnet losses, thus challenging thermal management. The magnet utilization is the best for V-shape rotors, but these rotors might have relatively lower corner speeds than the other two design types due to higher no-load voltage. On the other hand, the U-shape rotor design is a compromise between the V- and Double-V designs, offering some degree of design flexibility. The utilization of the hairpin winding technique in electric motors results in AC conductor loss, particularly during high-speed and high-frequency operations. This contributes to a faster decline in the output power beyond the base speed of the motor. Due to the advantages and disadvantages of different winding methods, the favoured choice for traction motors has been the use of stranded conductors with distributed windings. Figure 1 shows several stator designs of various EVs/HEVs using this preferred winding technique.



(a) Double-layer winding



(b) Hairpin winding

Figure 1. Stator windings: (a) BMW i3 2016, (b) and Toyota Prius 2017

The parameter of slot/pole/phase q holds a significant place in the design of machines as it accounts for multiple constraints in motor design, including the maximum fundamental frequency, high-speed losses, and mode order for NVH (noise, vibration, and harshness) performance. In particular, the greatest common denominator (GCD) between the slot and pole numbers determines the dominant vibration mode order. As the core deformation is inversely proportional to the fourth-order of mode order, higher mode orders pose less concern for NVH performance [17-20].

4. Traction inverter drive

Innovative power devices, groundbreaking materials, improved capacitor options, and heat sinks specifically designed for certain applications present a chance to substantially increase the power density and enhance the performance of traction inverter drives. However, implementing these new components comes with a set of design obstacles that must be overcome. This section details the advancements and characteristics of these components, as well as the challenges and remedies required for next-generation high-power density traction inverters.

4.1 Power Semiconductor Devices

Wide-bandgap (WBG) and ultra-wide-bandgap (UWBG) materials are considered to be disruptive technology for high-performance power electronic systems as they offer superior material properties. WBG materials such as SiC and GaN possess high-bandgap Eg, breakdown field Ec, saturation velocity vs, and thermal conductivity, which enable the development of power semiconductor devices that have increased power handling capabilities with smaller sizes and reduced losses compared to conventional unipolar and bipolar Si-based devices. Figure 2 depicts the specific on-resistance of a unipolar active power semiconductor drift region, such as MOSFETs, based on various semiconductor materials. It is important to highlight that SiC devices have been recognized as the primary solution for high switching frequency, high voltage, and high-temperature applications. A lateral enhancement-mode high-electron-mobility transistor (HEMT) structure based on GaN devices was introduced to the low-voltage (<600 V) power device market and placed on a Si substrate. This design comprises a GaN-AlGaN layer that forms a 2D electron gas, resulting in superior switching and conduction performance. Moreover, the Si substrate provides a cost-effective alternative to Si MOSFETs [21-23].

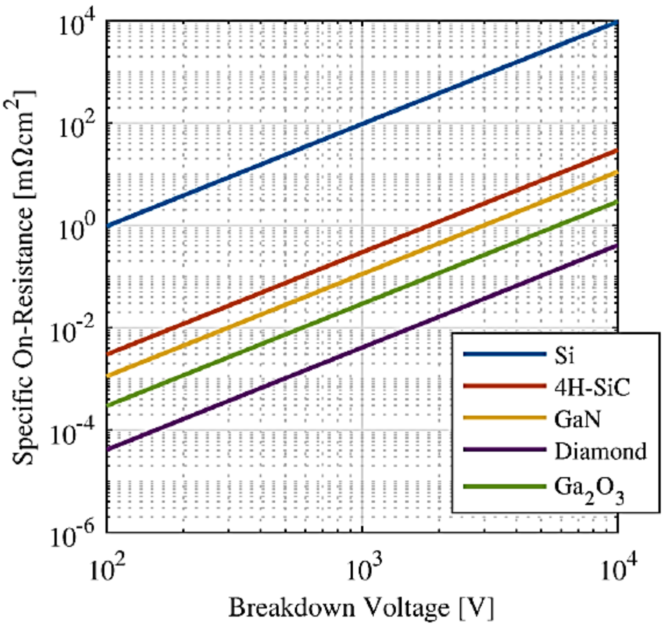


Figure 2. The Specific On-Resistance of a Unipolar Device's Drift Region

4.2 Integrated Power Modules

Power semiconductor modules play a critical role in transferring electric power between the source and load in inverters. The advent of WBG-based power semiconductor devices, such as SiC, MOSFETs, and GaN HEMTs, has significantly improved the efficiency of these systems. Despite this, the increased power demand from electrical loads, the higher power density of modules, and reduced chip size have led to a considerable amount of power dissipation in a small area. Consequently, the development of packaging materials, power module integration, and thermal management systems have emerged as a primary focus for the next generation of power electronic systems, particularly in areas related to electric vehicles. The diagram in Figure 3 depicts a cross-sectional view of a conventional power module and identifies its various structural components.

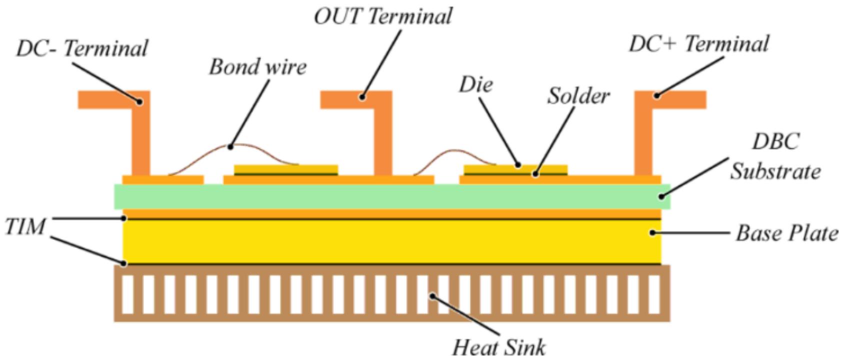


Figure 3. Conventional power module using a DBC-based substrate

The module is constructed using several materials including aluminium for bond wires, copper for electrical terminals, and a ceramic-based direct-bonded copper substrate (DBC). The structure comprises multiple layers of different materials, resulting in limited heat dissipation capabilities due to the number of layers and restricted lateral heat distribution. In this regard, all the packages utilized for producing SiC-based modules were created for Si-IGBT devices. Despite their low cost, established design maturity, and straightforward use by design engineers, these packages are unsuitable for high-performance power electronics packaging of WBG devices due to their high parasitic inductance for single-layer conductor layout and high thermal impedance caused by multiple material layers present between the device and the heat sink [19-23].

4.3 Inverter Design Optimization

To achieve high power density in traction drives and reduce the size of passive components, wide bandgap (WBG) devices are typically operated at high frequencies. However, the impact of high di/dt on parasitic inductances cannot be overlooked under fast switching conditions, particularly in multi-chip high-power modules. Consequently, it is necessary to address these challenges by optimizing designs while also utilizing advanced analytical tools to evaluate potential negative effects. The establishment of the commutation loop in an inverter is facilitated by the laminated DC bus and the DC-link capacitor bank. In some instances, multiple commutation loops may be present in the inverter. However, the DC bus voltage of the inverter is limited by the voltage overshoot that is caused by the energy stored in the parasitic inductance (Lp) seen by the drain and source power terminals of the power module during turn-off.

4.4 DC-Link Capacitors

Capacitors serve a critical role as passive components in traction inverters by maintaining the DC-link voltage, regulating current flow, and suppressing high-frequency current components. Most of the capacitors in a voltage source inverter (VSI) are employed to isolate the load from the power supply, leading to the capacitor's absorption of a substantial ripple current resulting from the inverter's switching action. The DC-link capacitor can account for up to 60% of the RMS load current in a three-phase VSI. As the capacitor bank needs to store a certain amount of energy to maintain a stable DC voltage level, it occupies a significant amount of space, thus limiting the inverter's power density. In EV traction applications, there are various types of capacitors available, which can be categorized into two main groups: electrostatic and electrolytic capacitors

5. Cutting-edge materials for advancing electric machines

To achieve the Department of Energy's (DOE) goal of a power density of 50 kW/L for traction electric machines, a comprehensive approach involving materials development, cooling techniques, and designs is necessary. The cost and availability of raw materials are also crucial factors that drive research and development efforts. In this context, emerging materials such as ultra-conductive copper (UCC) for windings, grain boundary diffusion (GBD) processed magnets, and low-loss lamination materials are being investigated. In the context of PM-type traction electric machines, sintered neodymium-iron-boron (NdFeB) magnets are preferred for their high energy density and knee-point well into the third quadrant of the B-H characteristics. However, the use of heavy rare earth (HRE) materials makes these magnets expensive. The addition of dysprosium (Dy) or terbium (Tb) which are also HRE elements - can improve the magnets' resistance to demagnetization and high-temperature performance. Nevertheless, the cost and instability in price, along with supply uncertainties associated with Dy and Tb, remain a significant concern for BEV/HEV manufacturers. Emerging materials are being explored for stator and rotor laminations, to enhance their magnetic properties and reduce core losses. This development is vital for achieving the desired objectives for next-generation high-speed electric machines [22-25]. One promising low-loss electrical lamination material is the 6.5% Si steel, which has been gaining attention for high-speed electric machines. The material displays lower specific core loss than conventional steel while retaining similar magnetic properties and has been employed in high-frequency transformers and inductors. However, the brittleness of this material during stamping hampers its utilization for mass production. GE has introduced a dual-phase material that can regulate permeability in selected areas, presenting a potential solution to overcome the brittleness limitation.

6. Impact of WBG devices on motor insulation

In the context of electric motors, high dv/dt voltage can have adverse effects on motor winding insulation in two ways. Firstly, due to an impedance mismatch between the inverter output cable and the motor, the motor terminal may experience a voltage higher than twice the nominal value. The extent of this over-voltage increases with longer cable length and faster rise time. Secondly, high dv/dt switching voltage leads to uneven voltage distribution across the turns and coils of a motor winding, potentially causing some insulation layers between winding turns to sustain higher voltage than others. This can result in partial discharge and gradual insulation breakdown.

The primary means of mitigating the effects of high dv/dt voltage on motor winding insulation is by positioning the traction inverter as near to the motor as possible. The Tesla Model 3 was the pioneer commercial electric vehicle (EV) to utilize SiC MOSFETs. A teardown was conducted by that the motor and inverter components are closely attached. The current research on integrating the motor and inverter will continue to reduce the distance between these components. The second mechanism of high dv/dt voltage causing uneven distribution of applied voltage across motor winding turns and coils can be managed by reinforcing the insulation material or by incorporating a dv/dt or sine-wave filter between the inverter and motor [25-28].

7. Conclusion

There remain numerous challenges to overcome in the development of inverters and motors to enhance the efficiency and affordability of future electric vehicles. Key objectives include achieving high power density to seamlessly integrate the electric drive with the battery foundation, accomplished through more advanced and integrated designs. It is critical to recognize that WBG-based inverters cannot simply replicate their Si-based counterparts; just as current BEV designs have diverged from conventional gas-powered vehicle designs. To meet the ambitious goals established for upcoming battery electric vehicles, there is a requirement to incorporate emerging materials and innovative designs. The introduction of WBG-based inverter drives and HRE-free machine designs will be essential for commercial viability with an emphasis on minimal manufacturing complexity to improve both cost-effectiveness and dependability. In addition, Electromagnetic interference (EMI) is anticipated to be more severe in WBG-based drive systems as compared to Si-based alternatives. To fully realize the advantages of WBG technology, it is essential to implement effective measures to mitigate electromagnetic interference (EMI) at the source and minimize the spread of noise. This requires innovations in both design and manufacturing to achieve high power density targets of 50 kW/L for the electric machine and 100 kW/L for the inverter drive.

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