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State-of-the-Art Electromagnetics Research in Electric and Hybrid Vehicles

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(*Invited Paper*)

Abstract—There is no doubt that electrified vehicles are superseding internal combustion engine vehicles for road transportation. Among them, electric vehicles (EVs) have been identified as the greenest road transportation while hybrid EVs have been tagged as the super ultra-low emission vehicles. In this paper, the definition, classification, merits and demerits of electric and hybrid vehicles are first introduced. Then, after revealing their multidisciplinary technologies and development trends, the state-of-the-art electromagnetics research in electric and hybrid vehicles are discussed, with emphasis on electric motors for electric propulsion, electric machine systems for hybrid propulsion, wireless power transfer technologies for park-and-charge a well as move-and-charge, electromagnetic interference and compatibility issues in EVs, electromechanical flywheels for energy storage and magnetic sensors for EV operation. Meanwhile, the development trend of these research areas is revealed.

1. INTRODUCTION

There have been various definitions of electric vehicles (EVs). For instance, EVs are generally classified as the pure EV (PEV) and hybrid EV (HEV) based on their propulsion systems, whereas they are also classified as the battery EV (BEV), HEV and fuel-cell EV (FEV) based on their energy sources. Sometimes, the BEV is loosely called the EV so that they are also named as the EV, HEV and FEV. In recent years, there has been a trend that EVs should first be classified by their propulsion devices, and then be further classified by their energy carriers and energy sources [1]. So, EVs are first classified as the PEV and HEV families based on their propulsion devices, namely the PEV solely adopts the electric motor for electric propulsion and the HEV uses both the electric motor and heat engine for hybrid propulsion. It should be noted that the general public prefers to loosely name the PEV as the EV and the HEV as the HV, leading to form the general term of electric and hybrid vehicles. Based on the variation of energy carriers and energy sources, the PEV family can be split into the BEV and FEV due to the use of batteries and fuel cells as their main energy sources, respectively. Taking into account the latest energy sources of capacitors (specifically dubbed ultracapacitors (UCs) or supercapacitors) and flywheels (specifically dubbed ultraflywheels (UFs) or ultrahigh-speed flywheels), the ultracapacitor EV (UCEV) and ultraflywheel EV (UFEV) are also members of the PEV family. On the other hand, based on the hybridization level between the electric motor and heat engine, the HEV family consists of five members: the micro hybrid, mild hybrid, full hybrid, plug-in HEV (PHEV) and range-extended EV (REV) in accordance with their increasing contribution from the electric motor for hybrid propulsion [2]. Among them, the micro, mild and full hybrids are termed conventional HEVs which are solely refueled with liquid fuel in filling stations, whereas the PHEV and REV are called gridable HEVs which can

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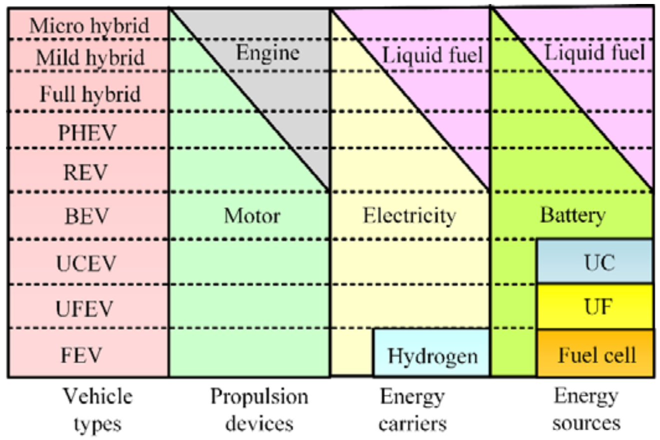


Figure 1. Classification of various EVs.

be recharged by electricity via charging ports or refueled with liquid fuel in filling stations. This classification is depicted in Fig. 1.

PEVs and HEVs have their merits and demerits as compared with existing internal combustion engine vehicles (ICEVs). The key merits are summarized as follows:

- They can effectively suppress harmful emissions such as nitrogen oxides and particulate matters, even taking into account the emissions to generate electricity.
- They can significantly reduce carbon emission, particularly when the fuel mix for electricity generation is mainly based on renewables.
- They can offer better energy diversification than ICEVs, especially those gridable hybrids can be refueled by liquid fuels and electricity which have excellent infrastructure support.
- They can offer higher well-to-wheel energy efficiency (namely from oil well to wheel motion) than ICEVs.

On the other hand, PEVs and HEVs have their individual shortcomings. Their key demerits are summarized below:

- Being the most mature PEV, the BEV suffers from the limited driving range, high initial cost and lack of charging infrastructure. Although more batteries may be installed to extend the driving range, the initial cost will be drastically increased.
- The BEV takes time for battery charging. When adopting fast charging, the installation cost is high and the charging process inevitably burdens the power system.
- As the BEV needs regular deep discharge, the battery life is generally shorter than the vehicle life. The renewal of batteries will further increase its effective lifetime cost.
- Due to the use of both the electric motor and engine, HEVs generally suffer from the system complexity for hybrid propulsion.
- Since the engine inherently offers low efficiency and narrow operating range, HEVs generally suffer from control difficulty in achieving optimal efficiency operation.

EVs are an integrated system involving multidisciplinary technologies — electrical engineering, mechanical engineering and chemical engineering. It can be split into three subsystems: energy system, propulsion system and auxiliary system. Among them, the energy system has been most actively developed in recent years where there are many innovations and advancements in the areas of energy sources, energy management and energy refueling. The development trends are to reduce the energy cost or increase the cost-effectiveness, to improve the energy storage or generation capacity, and to automate the recharging or refueling process. Meanwhile, the propulsion system has also been actively developed in recent years, focusing on the advancement of electric motors to improve the efficiency, torque density, power density and controllability, and the development of machine systems to optimally coordinate the hybrid propulsive powers created by the motor and engine. In addition, the auxiliary system is developed with emphasis on the areas of auxiliary power supply, power steering and temperature control, aiming to reduce the power consumption of vehicular electronics and enhance the vehicular manoeuvrability. This auxiliary system can readily be extended to conventional ICEVs.

Among various technologies for electric and hybrid vehicles, the electromagnetics play a very important role. Among various electromagnetics research activities for EVs, five main areas are identified: electric machines for propulsion, wireless power transfer for battery charging, electromagnetic interference and compatibility issues, electric flywheels for energy storage, and magnetic sensors for vehicular operation. The purpose of this paper is to give an overview of the corresponding state-of-the-art research, and to reveal the development trend.

2. ELECTRIC MACHINES FOR PROPULSION

Electric machines are the core technology for EVs that convert the on-board electrical energy to the desired mechanical motion. The requirements of electric machines for EVs are much more demanding than that for industrial applications. These requirements are summarized below:

- High torque density and high power density.
- High efficiency over wide torque and speed ranges.
- Wide speed range, covering low-speed creeping and high-speed cruising.
- Wide constant-power operating capability.
- High torque capability for electric launch and hill climbing.
- High intermittent overload capability for overtaking.
- High reliability and robustness for vehicular environment.
- Reasonable cost.

2.1. Electric Motors for Electric Propulsion

Figure 2 shows the classification of electric motors for electric propulsion in which the bold types are those that have been applied to PEVs, including the series DC, shunt DC, separately excited DC, permanent magnet (PM) DC, cage-rotor induction, PM synchronous, PM brushless DC (BLDC) and switched reluctance (SR) motors [3]. Basically, they are classified into two main groups — commutator and commutatorless [4]. The former simply denotes that they have a commutator and carbon brushes, while the latter have neither commutator nor carbon brushes. The development trend is focused on

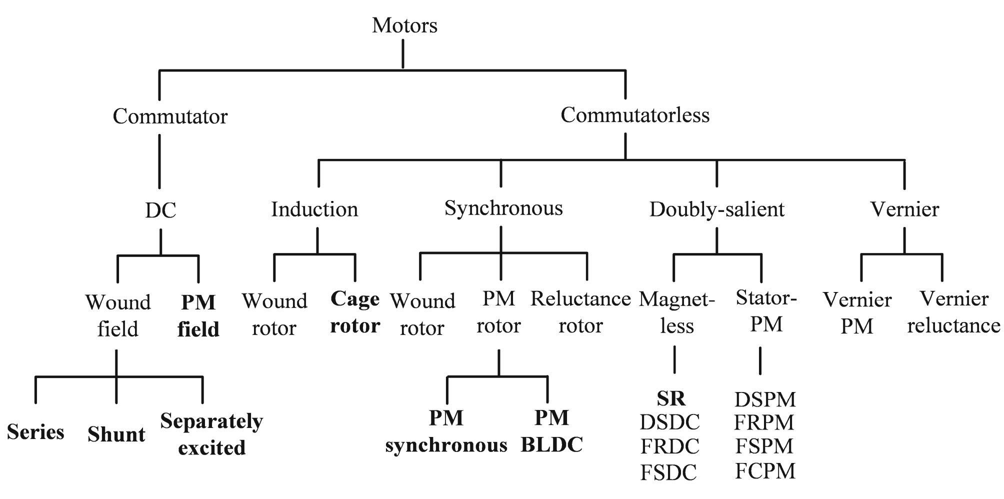


Figure 2. Classification of electric motors for electric propulsion.

developing new types of commutatorless or brushless motors, especially the class of doubly-salient motors and the class of vernier motors.

The key feature of doubly-salient motors is the presence of salient poles in both the stator and rotor. The SR motor is a kind of doubly-salient motors having the simplest magnetless structure. When incorporating PMs in the stator of doubly-salient motors, a state-of-the-art class of PM brushless motors is resulted — the stator-PM motors [5]. Since the rotor has neither PMs nor windings, this class of motors is mechanically simple and robust, hence very suitable for vehicular operation. According to the location of the PMs, it can be split into the doubly-salient PM (DSPM), flux-reversal PM (FRPM) and flux-switching PM (FSPM) motors. Additionally, with the inclusion of independent DC field windings in the stator for flux control, the class can be extended to the flux-controllable PM (FCPM) types. In recent years, they have been further extended to derive the partitioned stator FRPM motor [6] which can decouple the electric and magnetic loadings to achieve outstanding torque density, and the multiphase FSPM motor [7] which can offer high fault-tolerant capability. Furthermore, when the PM poles are replaced with DC field windings aiming to get rid of those expensive PM material [8] and provide flexible flux control, the resulting doubly-salient DC (DSDC), flux-reversal DC (FRDC) and flux-switching DC (FSDC) motors are emerging types of magnetless motors [9]. By electronically switching between two operation modes, namely the multitooth bipolar-flux operation for high-torque low-speed situation and the single-tooth unipolar-flux operation for low-torque high-speed situation, an electronic-geared magnetless motor has recently been developed for electric propulsion [10].

The key feature of vernier motors is the use of vernier effect to amplify the output torque while stepping down the speed, leading to a unique class of brushless motors dedicated to low-speed high-torque direct-drive application. There are two main classes of vernier motors, namely the vernier PM (VPM) and vernier reluctance (VR). The VPM motor has three types, depending on the location of PMs: the rotor-PM type with all PMs mounted on the rotor, the stator-PM type with all PMs mounted on the stator, and the all-PM type with PMs mounted on both the rotor and stator [11]. As the rotor-PM VPM motor is most mature, it is loosely called as the VPM motor. The stator-PM VPM motor is commonly termed the vernier hybrid motor. In recent years, the VPM motor has been further extended to provide the controllable air-gap flux density and homopolar structure [12]. It should be noted that the VR motor is structurally similar to the SR motor, but they operate differently. Because of the vernier effect, it mainly serves as a low-speed high-torque magnetless motor.

All machine topologies developed for the conventional radial-flux morphology can readily be extended to other morphologies such as the axial-flux morphology and transverse-flux morphology, which can further improve the torque density. Recently, an axial-flux DSDC (AF-DSDC) motor has been developed for in-wheel direct drive [13]. It employs the single-stator double-rotor structure to solve the problem of large axial force exerted on the stator by the rotor. Table 1 shows a quantitative comparison of three state-of-the-art magnetless motors, namely the SR, DSDC and AF-DSDC motors with respect to the DSPM, under the same peripheral dimensions. It can be found that the AF-DSDC motor can offer comparable rated power and hence torque densities as the DSPM motor; meanwhile,

Table 1. Comparison of state-of-the-art magnetless motors with PM counterpart.

	SR	DSDC	AF-DSDC	DSPM
Radial outside diameter (mm)	381	381	381	381
Radial inside diameter (mm)	100	100	100	100
Axial stack length (mm)	195	195	195	195
Air-gap length (mm)	0.5	0.5	0.5	0.5
Rated power (kW)	2.2	2.6	4.8	5.2
Torque/mass (Nm/kg)	0.51	0.61	1.13	1.21
Torque/size (kNm/m^3)	4.12	4.85	8.97	9.51
Material cost (USD)	208.4	209.8	239.5	411.9
Torque/cost (Nm/USD)	0.34	0.41	0.65	0.39

the AF-DSDC motor is much more cost-effective than the DSPM motor. Although the transverse-flux morphology can offer the highest torque density, the corresponding motor structure is very complicated which limits its manufacturability and practicality for EVs.

2.2. Electric Machine Systems for Hybrid Propulsion

There are two main machine systems for hybrid propulsion: the integrated-starter-generator (ISG) for the micro and mild hybrids of conventional HEVs, and the electric variable transmission (EVT) for the full hybrid of conventional HEVs as well as the PHEV and REV of gridable HEVs [14]. The ISG machine system needs to offer not only the conventional features of engine cranking and electricity generation, but also the hybrid features of idle stop-start, regenerative braking and power assistance. So, the corresponding machine design, analysis and control are very demanding. The EVT machine system functions to offer electrically controllable power transfer from the engine to the wheels with continuously variable transmission, hence providing all hybrid features including the electric launch, idle stop-start, regenerative braking and power assistance as well as achieving the highest fuel economy.

On top of the requirements of electric motors for electric propulsion, the ISG machines have some additional requirements:

- High-efficiency generation over wide speed range.
- Good voltage regulation over wide-speed generation.
- Capable of being integrated with the engine.

The induction machine and PM brushless machine based ISG systems are becoming mature for mass production, which can further reduce the manufacturing cost. The development trend of ISG machines focuses on further improving the operating performances such as the starting torque, constant-voltage generation, motoring and generation efficiencies, robustness and cost effectiveness. Some state-of-the-art ISG machines are the PM hybrid brushless machine which can allow flexible control of air-gap flux density to improve the starting torque and constant-voltage generation [15], the AF-DSDC magnetless machine which does not require any expensive PM material while offering comparable torque density to improve the robustness and cost effectiveness [16], and the compressed winding PM brushless machine which can increase the conductor fill factor to improve the efficiency and thermal conductivity [17].

The planetary-geared EVT (PG-EVT) machine system is almost exclusively used for the commercially available full hybrid and gridable hybrids, which was first developed by Toyota for its Prius [18]. The key is to make use of planetary gearing to split the engine power into the mechanical path and the controllable electrical path, hence enabling the engine to continuously operate at the optimal condition. However, this kind of PG-EVT machine systems desires two electric machines and inherits the fundamental drawback of planetary gearing, namely the transmission loss, gear noise and need of regular lubrication.

In order to get rid of this mechanical gearing, various double-rotor machines are developed to perform the desired power split of the engine, hence forming the gearless double-rotor EVT (DR-EVT) machine systems [19, 20]. However, this kind of DR-EVT machine systems needs to employ slip rings and carbon brushes to extract the energy from the inner rotor, which suffers from the reliability concern and need of regular maintenance.

By the same token, various double-stator machines can also be employed to perform the desired power split, hence forming the double-stator EVT (DS-EVT) machine systems [21]. However, the corresponding double-stator machine cannot directly feed the driveline so that an additional motor is mandatory.

By replacing the planetary gearing with magnetic gearing, the resulting magnetic-geared EVT (MG-EVT) machine systems can inherit the distinct advantages of magnetic gearing, namely the high transmission efficiency, silent operation and maintenance free, while avoiding to use of slip-rings and carbon brushless [22, 23]. Nevertheless, this kind of pseudo-gearless, brushless EVT machine systems exhibits a complicated structure, and the required precision for manufacture is demanding.

Some key features of the four state-of-the-art EVT machine systems are summarized in Table 2. It can be observed that they have their individual advantages and disadvantages. In near term, the DR-EVT is very promising to compete with the PG-EVT in the market of HEVs, and in long term, the MG-EVT is capable of superseding the PG-EVT for those high-performance HEVs.

Table 2. Comparison of state-of-the-art EVT machines systems.

	PG-EVT	DR-EVT	DS-EVT	MG-EVT
No. of machines	2	1	2	1
No. of converters	2	2	3	2
Power density	Low	Medium	Low	High
Efficiency	Medium	Medium	High	High
Maintenance	Yes	Yes	No	No
Noise	High	Medium	Low	Low
Complexity	Medium	Medium	Medium	High
Initial cost	Low	Medium	Medium	High

3. WIRELESS POWER TRANSFER FOR BATTERY CHARGING

In recent years, many researchers have proposed various methods to alleviate the problem of short driving range per charge of the BEV, focusing on the development of more convenient chargers. Rather than simply building more charging stations and adopting faster battery chargers, the use of wireless power transfer (WPT) for battery charging can greatly facilitate the charging process. Most importantly, because of the absence of metallic contacts, possible electrocution during the charging process can be totally eliminated, which can enable the BEV outperforming the ICEV in terms of user safety for self-service recharging or refueling [24].

3.1. Wireless Power Transfer for Park-and-Charge

There are two main categories of WPT: the far-field and near-field. For BEV application, the near-field inductive power transfer (IPT) is almost exclusively used [25, 26]. Fig. 3(a) shows the principle of traditional IPT for battery charging based on the magnetic coupling between two coils of a high-frequency transformer. One of the coils is installed in the charger coupler while the other is embedded in the vehicle inlet. However, the corresponding core losses and electromagnetic interference are of concern. For instance, a well-known but obsolete IPT-based BEV charger, Magne Charge, delivered 6.6 kW at an efficiency of 86% with a frequency of 80–300 kHz within the charger [1].

In order to facilitate the park-and-charge (PAC) process for the BEV, the IPT technology is extended to be plugless, in which the primary coil is installed on the floor of a garage or in a parking lot

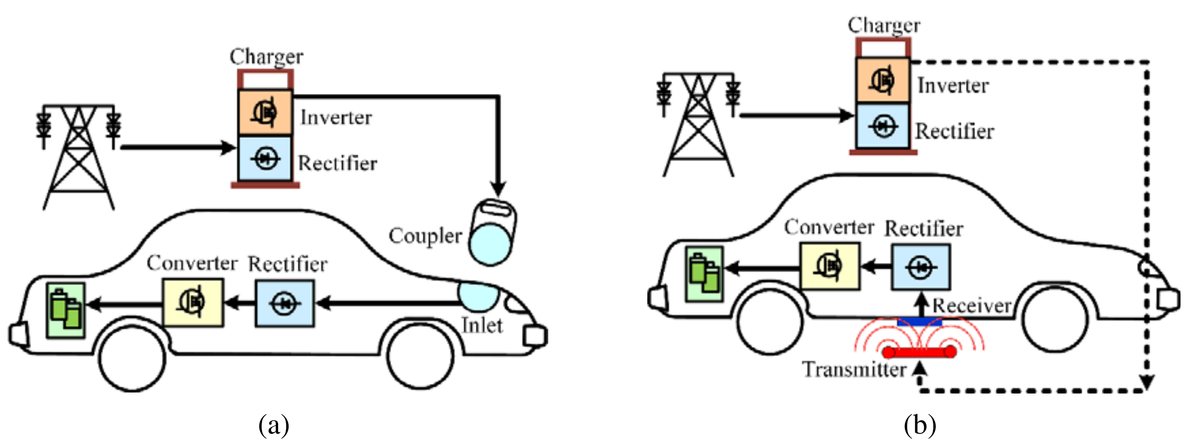


Figure 3. Inductive power transfer based park-and-charge: (a) Transformer coupling. (b) Magnetic resonant coupling.

and the secondary coil is installed on the vehicle as shown in Fig. 3(b). The driver needs no bothering about those cumbersome and dangerous charging cables. The use of this system is very easy and the charging process takes place automatically once the driver parks the BEV correctly. This plugless PAC not only increases user convenience, but also offers a means of overcoming the standardization of charging plugs. Due to the existence of a large air-gap or clearance between the primary and secondary coils, the transformer coupling IPT technology is ill-suited. Based on magnetic resonant coupling, the primary and secondary coils having the same resonant frequency can wirelessly transfer power efficiently with high power density, while dissipating relatively little energy in non-resonant objects such as vehicle bodies or drivers [27]. Recently, a 4-kW 140-kHz plugless PAC prototype has been tested, which can achieve the system efficiency of 96.6% with an 8-cm air-gap [28].

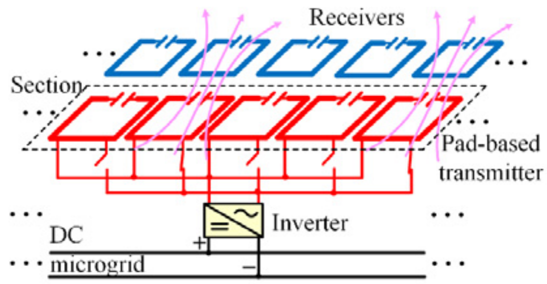
Latest research and development of WPT for PAC are active and diversified, such as compensating the misalignment between magnetic couplers, realizing bidirectional WPT between chargers and BEVs, integrating power transfer and information transfer within the same channel. Some state-of-the-art works are summarized below.

- For realistic PAC, the magnetic coupler design plays a key role for effective WPT. For instance, the compound primary pad using uneven pitch distances of the spiral winding has been proposed, which can offer a uniform magnetic flux density at most of the charging area, hence solving the problem of misalignment [29]. Meanwhile, the bipolar primary pad has been developed, which can interoperate with simple secondary pads to achieve power transfer with large lateral tolerance [30].
- Since BEVs can serve as mobile power plants to support and stabilize the power grid with renewables, the development of vehicle-to-grid (V2G) technology is promising [31]. By incorporating the WPT into the V2G, a bidirectional power interface has been developed to facilitate simultaneous charging and discharging of multiple BEVs [32]. Various bidirectional resonant inverters have recently been developed for wireless V2G, aiming to improve the power level, power flow control and fault-tolerant ability [33].
- The simultaneous wireless power and information transfer (WPIT) technology is being actively developed for BEV charging, which desires power transfer from the charger to the vehicle and data communication between the charger and on-board battery management system. A WPIT system has been proposed in which the fundamental component of the triangular current waveform is employed to transfer power, and its third-order harmonic component is selected to transfer information [34].

3.2. Wireless Power Transfer for Move-and-Charge

Rather than stopping or parking, the BEV prefers to be wirelessly charged during moving. Namely, an array of power transmitters are embedded beneath the roadway (so-called the charging zone or lane) while a receiver is mounted at the bottom of the BEV. This move-and-charge (MAC) technology has high potentiality to fundamentally solve the long-term problems of the BEV. Namely, there is no need to install so many batteries in the BEV, hence dramatically cutting its initial cost; and the BEV can be conveniently charged at the charging zone during driving, hence automatically extending the driving range. Differing from PAC, the system configuration for MAC is more challenging. Since the length of electrified roadway is in terms of kilometers, the number of transmitters buried beneath the road should be minimized. Meanwhile, the electrified roadway should be designed to have minimum power loss, and be maintainable and scalable when necessary. More importantly, the system must be able to achieve WPT with high efficiency (over 90%) and sufficient air-gap length (over 20 cm) for roadway-powered BEVs.

The transmitters installed beneath the road surface can be either pad or rail design. The pad design includes many primary pads where the size of each pad is equal to or less than that of a vehicle. It can utilize power inverters and sensors to separately excite the primary pads so that only those BEVs which have been authorized to receive energy can be wirelessly charged. Alternatively, based on one power inverter per section, the primary pads can be separately excited by using power switches and sensors as shown in Fig. 4(a). These pad-based transmitters inevitably involve a large amount of primary pads, power inverters or power switches and sensors, thus suffering from huge investment cost and high installation complexity. Although the reflexive segmentation layout can partially solve this problem by



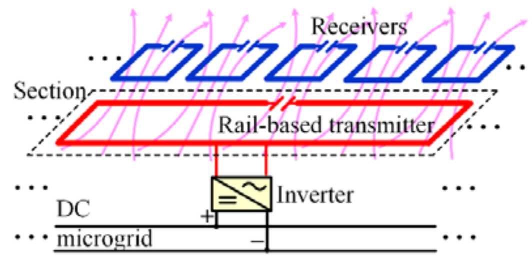


Figure 4. Inductive power transfer based move-and-charge: (a) Multiple primary pads per section as transmitter. (b) Single primary rail per section as transmitter.

using only one power inverter [35], it still needs a large amount of primary pads. In contrast, the rail design involves only a primary rail or actually a long primary coil and a power inverter to feed multiple BEVs as shown in Fig. 4(b), which takes the definite advantage of much lower investment cost and much lower installation complexity than the pad design. For the sake of more flexible maintainability and scalability, the rail design usually adopts the arrangement of sectionalized roadway in which it uses one power inverter per section to feed multiple BEVs.

There are many challenges to be tackled before the realistic application of MAC. First, the efficiency of WPT heavily depends on the vertical distance and horizontal misalignment between the primary and secondary coils. Since such distance and misalignment are inevitably time-varying and significantly affected by the road condition and vehicle payload, the power converter that excites the transmitter needs to be dynamically controlled to maintain high-efficiency power transfer. Second, the effectiveness of MAC operation heavily depends on the coverage of WPT as well as the position and speed of vehicles running on the charging zone. The location of transmitters needs to be optimized in such a way that the electromagnetic field intensities at different locations over the charging zone are uniform. Third, as there are many BEVs running on the electrified roadway, the MAC operation needs to distinguish which BEVs are authorized to retrieve wireless power or to prevent unauthorized vehicles from stealing the energy.

Because of the potentiality to fundamentally solve the long-term problems of BEVs, research and development of MAC technology have been overwhelming [36]. Some state-of-the-art works for MAC are summarized below.

- The online electric vehicle (OLEV) project conducted by KAIST has successfully implemented the rail-based MAC system. It has solved various MAC problems such as high-frequency current-controlled inverters, continuous power transfers, and cost-effective improvement [37]. Innovative coil designs and roadway construction techniques make the system efficiency of the OLEV reach up to 83% at an output power of 60 kW with a resonant frequency of 20 kHz. Meanwhile, the air-gap of 20 cm and lateral tolerance of 24 cm can be achieved.
- Due to the mobility of the BEV, the misalignment between the primary and secondary coils of the pad-based MAC system inevitably affects the performance of existing WPT techniques. The homogeneous WPT technique has been proposed, which utilizes the alternate winding design to gaplessly assemble primary coils to enhance the magnetic flux density, and the vertical-and-horizontal secondary coil to improve the capability of acquiring energy especially in the area of the coils gap [38]. Hence, it can effectively improve the power transfer performance of this pad-based MAC system.
- In order to allow authorized BEVs perform charging and avoid unauthorized BEVs stealing wireless power when they are running on the rail-based MAC system, the energy encryption technique has been proposed [39]. Namely, the operating frequency is purposely adjusted to follow a predefined sequence over a pre-defined frequency band (so-called the security key) while the primary rail is synchronously tuned to have the resonant frequency matching with the operating frequency, the transmitted energy is thus encrypted. When the secondary coil is also synchronously tuned to have the same resonant frequency in accordance with the security key, the authorized BEV can receive

the desired energy; otherwise, without the knowledge of security key, the unauthorized BEV cannot decrypt the encrypted energy or receive the desired energy.

4. ELECTROMAGNETIC INTERFERENCE AND COMPATIBILITY IN ELECTRIC VEHICLES

Conventional ICEVs generally suffer from two main types of electromagnetic interference (EMI): the broadband EMI from the ignition system and starter motor and switches, and the narrowband EMI from the electronic devices [40]. Differing from ICEVs, BEVs involve many electric devices which are in close proximity. They generate high-level low-frequency EMI. Thus, it is inappropriate to treat electromagnetic compatibility (EMC) of BEVs as that of ICEVs. Additionally, the charging facilities for BEVs create an unprecedented EMI problem that is absent in ICEVs. Since the EMI problem will affect the performance of BEVs and may even be detrimental to the health of passengers and pedestrians, how to reduce the EMI and improve the EMC in BEVs have attracted numerous research activities in recent years.

4.1. EMI and EMC of Critical Components in BEVs

The electric propulsion system consists of a high-voltage battery, a high-frequency converter, a high-power electric motor and many sophisticated electronic devices as well as many shielded and unshielded high-power cables distributed around the vehicle [41]. These components are actually the main EMI sources in a BEV. Among them, the power converter is the major EMI source, which involves high-voltage, high-current and high-frequency switching processes.

For electric propulsion, the system voltage is purposely elevated to a high level, as high as 900 V, aiming to reduce the operating current and hence the conduction loss. This high-voltage system is isolated from the low-voltage system for electronic devices. As space for wiring harness is limited inside the vehicle, the high-voltage and low-voltage cables are arranged closely to each other, resulting in crosstalk between different cables. Thus, in order to assess the EMI and EMC in BEVs, it is desirable to investigate high-frequency modeling of power converters, electric motor, battery, shielded and unshielded cables as well as their coupling paths [41]. The development of line impedance stabilization networks (LISNs) that can handle high voltages is needed. Recently, the influence of high-voltage LISNs on EMC performance in EVs has been investigated [42], which indicates that the LISN should adapt to the characteristic impedance of the high-voltage cables applied.

Since electric motor drives rely on using power inverters with high-speed pulse width modulation switching operation, surge voltage inevitably occurs at the motor terminals. The resulting EMI noise such as the radiated noise and the shaft current may cause malfunction of the vehicle controller and damage of motor bearings. Recently, an EMI noise controller has been developed for BEVs, which is attached on the motor terminals to simultaneously suppress the surge voltage, shaft current and radiated noise [43]. Meanwhile, a digital active EMI filter has been developed for EVs, which can be integrated into the digital controller of a DC-DC converter for charging the low-voltage battery and can achieve significant EMI attenuation [44]. Hence, the passive EMI filter can be eliminated, which greatly reduces the size and weight of the overall motor drive.

At present, wide bandgap power devices, such as gallium nitride (GaN), are becoming popular in automotive industry due to their low on-state resistance and fast switching capability. However, the corresponding high dv/dt has the potential to deteriorate the EMI of power converters and thus may fail the EMC in BEVs. Thus, the EMI and EMC issues that are faced with the adoption of GaN power devices in BEVs should be addressed in an urgent manner. Very recently, a GaN-based half-bridge DC-DC converter that is widely used between the high-voltage bus and low-voltage bus of a BEV has been studied [45], which indicates that the common-mode noise is similar to that of a MOSFET-based converter while an efficiency improvement by 0.5–2.5% can be achieved.

4.2. EMI and EMC of Wireless Chargers for BEVs

Apart from the EMI sources inside the vehicle body, there are external EMI sources outside the vehicle body that can also affect the performance of BEVs and may even be detrimental to the health of passengers and pedestrians. These external EMI sources are mainly from the battery chargers, overhead lines, underground cables and even other BEVs. Among them, the wireless charging facilities are the major EMI source.

When WPT is applied to battery charging for BEVs, a strong electromagnetic field in the range of several tens to hundreds of kilohertz is intentionally generated to transfer power from several kilowatts to tens of kilowatts. Because of such high-power WPT, the biological effects of this strong electromagnetic field on the human body are utmost important. Although a large amount of research have been dedicated to the study of human exposure to some electromagnetic devices for WPT with the operating frequency from megahertz to gigahertz [46], relevant research on WPT in the low kilohertz range is at the crawling stage.

Since the strong electromagnetic field for wireless charging may induce high electromagnetic fields in the body tissues of persons nearby, it is crucial to identify conditions under which the WPT system can demonstrate the compliance with international safety guidelines set by the International Commission on Nonionizing Radiation Protection (ICNIRP). Recently, the compliance approximation formulae of the close-range WPT system operating at 100 kHz have been derived, which allow reliable estimation of conservative exposure values [47]. Meanwhile, an evaluation of the electromagnetic fields in the human body exposed to the wireless charging system for BEVs has been investigated, which can examine the compliance of EV charging systems with respect to human electromagnetic exposure limits [48].

Rather than simply assessing the EMI and EMC issues on BEVs, many researchers have developed various techniques to shield the leakage magnetic field from the WPT system, such as the conductive shielding, magnetic shielding and active shielding. A state-of-the-art approach to suppressing EMI during wireless charging is the resonant reactive shielding, which has been developed to suppress the electromagnetic field leakage induced from the pad-based WPT system [49]. As shown in Fig. 5, since the main magnetic field created by the transmitter and receiver coils can readily be shielded by using a metal plate mounted on the bottom surface of the vehicle, the leakage magnetic field is guided parallel to the road surface and passes through the resonant reactive shield coils in such a way that the induced magnetic field in each shield coil can cancel the incident magnetic field. Hence, the magnetic field leakage can be effectively suppressed without consuming additional power. To cater for various operating conditions in a real BEV, the shield capacitance can be online tuned by using a switched capacitor array to suppress the leakage magnetic field.

Since the pad-based WPT system suffers from the use of a large amount of primary pads, power inverters or power switches and sensors for dynamic wireless charging of BEVs (namely MAC), the track-based WPT system is preferred. However, as the receiver coil of each BEV covers only a small portion of the track, it suffers from severe EMI. Three state-of-the-art active electromagnetic field cancellation methods have been proposed and implemented in the track-based WPT system, namely the independent self electromagnetic field cancellation, the 3-dB dominant electromagnetic field cancellation and the linkage-free electromagnetic field cancellation [50]. For the I-type track, cancellation coils are installed at the secondary side and no cancellation coil is required for the primary side. As a result, the electromagnetic field at a distance of 1 m from the receiver becomes under 44 mG for the maximum power of 12 kW. Hence, the human exposure to electromagnetic field can be significantly suppressed.

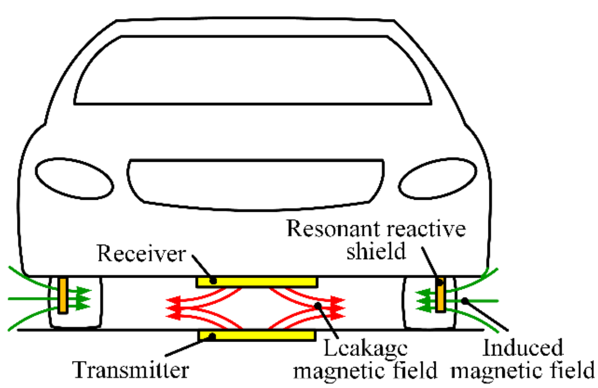


Figure 5. Resonant reactive shielding for wireless charging.

5. ELECTRIC FLYWHEELS FOR ENERGY STORAGE

While most popular energy storage devices for EVs rely on electrochemical means such as the battery, fuel cell and UC [24], there are two emerging ones based on electromagnetic means — the UF and superconducting magnetic energy storage (SMES). A comparison among them in terms of key performance indices, namely the specific energy, specific power, efficiency, lifetime, safety cost and maturity, is shown in Table 3, where a point grading system ranging from 1 (lowest) to 5 (highest) is adopted. It can be found that the UF possesses some distinct merits for EV applications, namely very high specific power, practically unlimited lifetime and very high efficiency as well as high robustness and easy monitoring of the state of charge. On the contrary, the SMES suffers from the drawbacks of very low specific energy and very high cost which make it ill-suited for EVs.

Table 3. Comparison of various EV energy storage devices.

	Battery	Fuel cell	UC	UF	SMES
Specific energy	4	5	2	3	1
Specific power	2	1	5	4	4
Efficiency	2	3	5	4	4
Lifetime	1	3	5	5	5
Safety	5	4	3	3	3
Cost	1	4	2	3	5
Maturity	5	3	4	3	1

5.1. On-Board Energy Storage

A flywheel energy storage system (FESS) stores energy in the form of kinetic energy based on a rotating mass driven by an electric machine. Since the kinetic energy is proportional to the square of rotating speed, the flywheel prefers to spin at extremely high speeds — so-called the UF. Fig. 6 shows its schematic structure, which consists of an electric machine serving as a motor during charging and as a generator during discharging, a power electronic circuit connected to the machine stator, a flywheel coupled with the machine rotor, two magnetic bearings holding the high-speed rotor/flywheel without physical contacts, and a vacuum environment serving to eliminate the windage loss. Since the specific energy of UFs is not high enough to serve as the sole energy source for EVs, the FESS generally needs to work as an auxiliary energy source with the battery so that two back-to-back converters are necessary. Namely, an AC/DC converter is coupled with a DC/AC converter via a DC link, which is connected with the battery.

The key component of this FESS is the electric machine, which needs to satisfy some stringent requirements: high power density, high efficiency, very wide speed range and high robustness. The existing electric machines that have been widely adopted for electric propulsion cannot meet these stringent requirements. For instance, the induction machine inherently suffers from relatively low efficiency and low power density; particularly, its high rotor loss is very problematic when the rotor is spinning in vacuum environment. Meanwhile, the PM synchronous machine suffers from the difficulty in mounting PM pieces on the rotor; particularly, its centrifugal force exerted on PM pieces is huge when spinning at high speeds. The development trend is to adopt the magnetless machines and stator-PM machines where the rotor is simple iron core, leading to minimum rotor loss and outstanding robustness.

A state-of-the-art magnetless machine for the FESS is the synchronous reluctance machine, which adopts an axially laminated rotor with alternating layers of ferromagnetic and nonmagnetic steel to provide the saliency ratio of 9 [51]. Because of the definite advantages of high-speed capability, high robustness and low cost, it has been designed to offer 60 kW at 48,000 rpm for the FESS in EVs. Another state-of-the-art magnetless machine for the FESS is the homopolar machine, which not only offers the features of high-speed capability, high robustness and low cost, but also the merit of very low zero-torque spinning losses [52]. A prototype has been demonstrated to offer an efficiency of 83% at

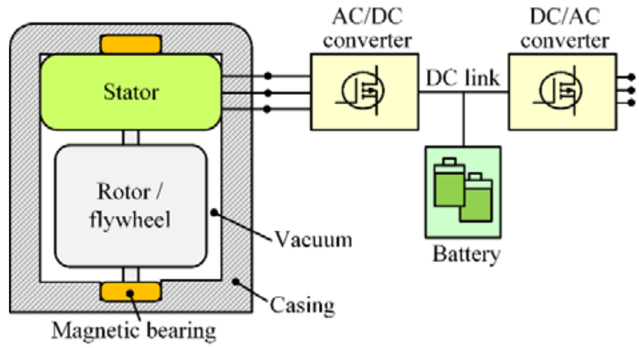


Figure 6. Flywheel energy storage system.

9.4 kW over 30,000–60,000 rpm. Recently, the homopolar machine has been further extended to adopt the outer-rotor topology, hence improving the energy density for the FESS [53].

Inevitably, the use of mechanical bearings to support the rotor/flywheel of the FESS suffers from some severe problems: high friction and associated energy losses, need of regular maintenance and replacement, and limits in both the rotor/flywheel weight and the rotating speed. In order to realize the desired FESS, the use of magnetic bearings is necessary, which serves to levitate the rotating shaft by magnetic forces, hence eliminating the bearing friction, maintenance requirement as well as weight and speed limits. There are two main types of magnetic bearings: passive and active. The passive magnetic bearing consists of PMs that support the weight of the rotor/flywheel by repelling forces. However, it generally suffers from the problem of instability. The active magnetic bearing consists of electromagnets produced by coils that can adjust the electromagnetic forces based on the shaft position, hence achieving stability by using feedback control. Thus, it inevitably involves additional hardware and complex control.

Various passive magnetic bearings were developed, aiming to provide stable magnetic levitation for the FESS. A state-of-the-art passive magnetic bearing that consists of PMs coupled with a Halbach array stabilizer can stably levitate the rotor/flywheel in all directions [54]. The levitation system makes use of two pairs of annular ring PMs which provide an upward magnetic levitation force to counteract the downward gravitational force of the rotor/flywheel. The Halbacharray stabilizer makes use of two stabilization coils shifted in angular position with respect to one another and centered in the vertical direction between two rotating Halbacharrays. Future works will involve alternative stabilizer designs and assessments of instability modes.

Many varieties of active magnetic bearings have been researched over the past two decades. In most designs, the relationship between bearing force and applied current is highly nonlinear and varies with the rotor position and magnetic saturation level. The applied current is also limited by thermal consideration. These restrictions make active magnetic bearings be unfavorable in terms of force-to-weight ratio when compared with mechanical bearings. A state-of-the-art active magnetic bearing employs the axial-magnetomotive force parallel-airgap serial flux concept that exploits high bearing force from a number of parallel ironless stator and PM rotor discs [55]. Because of the absence of iron in the active component, the bearing force and applied current is close to linearly related Future works will involve control strategies and sensorless technologies to achieve stable levitation.

5.2. Off-Board Energy Storage

In the foreseeable future, batteries are the main energy source of the PEV. In order to alleviate the problem of short driving range per charge, the fast charging scheme has been widely used for the BEV. It generally adopts DC 200–450 V, 80–200 A, 36–90 kW, and performs at the dedicated fast charging station. It only takes 20–30 minutes to charge 80% of the battery usable capacity [24]. However, it causes an additional burden to the power grid, especially during daytime peak hours. In order to mitigate this adverse effect, the fast charging station can be equipped with local energy storage system, which provides the power required to sustain the fast charging scheme of the BEV without overloading the power grid. Although the battery energy storage system (BESS) has been widely adopted for power system load leveling, it suffers from service life degradation, especially for the fast charging station that is characterized by deep and frequent cycling. Compared with the BESS, the FESS takes the definite advantages of higher efficiency higher power density and virtually no degradation Recently, the fast charging stations equipped with the FESS have been proposed to provide flexible load control reserves managed by the distributed system operator (DSO), which can manage loads to support the overall grid stability and better optimize the power generation resources [56].

Differing from the on-board FESS,the off-board FESS generally offers much higher power and energy ratings while the corresponding size and weight are no longer stringent. Their relevant components are essentially the same. Nevertheless, because of such high power and energy ratings, it becomes justifiable to incorporate high temperature superconducting (HTS) technology into the off-board FESS requiring cryogenic temperatures (below -150°C).

Recently, a high-speed superconducting bearingless machine has been proposed for the FESS [57]. It adopts a homopolar configuration in which two pairs of stator and rotor segments artfully share the same stator and rotor yokes while the rotor iron poles are deployed in an interleaved manner. The stator accommodates three types of windings, namely the armature winding for torque generation, the field winding for air-gap flux production, and the suspension winding for bearingless operation. The field winding adopts BSCCO-2223 HTS coils which can offer the current density up to $100\,\mathrm{A/mm^2}$. Being located in the stator, it can easily be cooled with an off-the-shelf Gifford-McMahon cryocooler. By adjusting the DC current in the HTS field winding, the amplitude and polarity of the air-gap flux density can be flexibly controlled, hence achieving effective flux weakening when motoring at ultrahigh-speeds and good voltage regulation when operating as a generator.

Apart from using the HTS material as conductors for electric machines, it has a unique diamagnetic property that can be utilized to stably levitate the rotor without using any control system for positioning. Recently, a realistic 300-kW FESS using the HTS magnetic bearing has been developed, which was claimed to be the world's largest-class FESS in 2015 [58]. In this FESS, the rotor coupled with three YBCO HTS plates are levitated by five REBCO HTS coils located in the stator. The levitation force depends on the current applied to the HTS coils. The corresponding HTS magnetic bearing can stably levitate 4000-kg load when a current of 74 A is applied. The stability and durability have been confirmed by the long-term operation test of over 1500 hours.

6. MAGNETIC SENSORS FOR VEHICULAR OPERATION

Magnetic sensors function to detect changes and disturbances in magnetic fields that have been created or modified by objects or events. Hence, presence, direction, rotation, angle and electric current can all be detected without physical contacts. There are many approaches for magnetic sensing [59]. Each approach has its merits and demerits for various applications. In recent years, magnetoresistive magnetic sensors have been developed for vehicular applications, because they are sensitive, small and more immune to environmental factors such as rain, wind, snow or fog, hence offering definite advantages over other vehicular sensing systems based on video cameras, ultrasound or infrared radiation. Also, because of their accurate, sensitive and integratable feature as well as inherently galvanic isolation, they are attractive for measuring critical component parameters in EVs. The commercially available magnetoresistive magnetic sensors, in the order of technical advancement, are the anisotropic magnetoresistive (AMR), giant magnetoresistive (GMR) and tunneling magnetoresistive (TMR) sensors.

6.1. Detection of Vehicle Occupancy and Speed

Earth's magnetic field can be distorted by any metallic object such as a vehicle. Distortions caused by vehicles can readily be measured by magnetic sensors. These measurements are then processed and used for vehicular detection. The PATH program of the University of California, Berkeley has laid the foundation on using magnetoresistive magnetic sensors for traffic measurement and vehicle classification [60]. In addition to vehicle count, occupancy and speed, the magnetic sensors yield traffic information such as vehicle classification that cannot be obtained from using inductive loops.

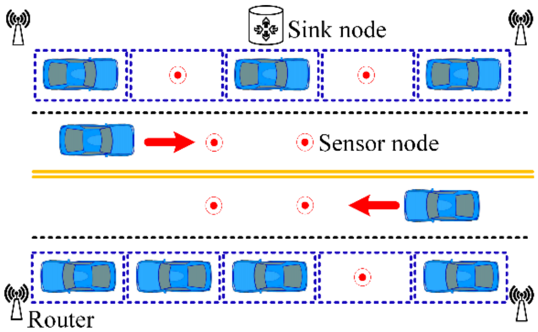


Figure 7. Vehicle static and dynamic detections using magnetic sensors.

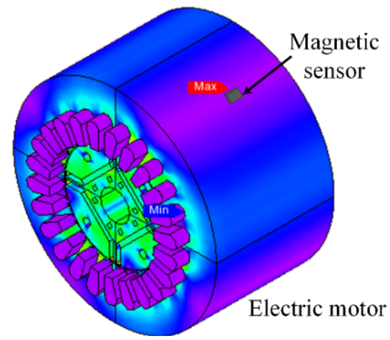


Figure 8. Non-invasive load monitoring of electric motor using magnetic sensor.

Figure 7 depicts two promising applications of magnetic sensors for vehicle detections: static and dynamic, which are mainly used for vehicle parking detection and vehicle speed estimation. There is wireless sensor network, which consists of magnetic sensor nodes, routers, and a sink node. Each sensor node, which is composed of a magnetoresistive sensor, transmitter, microcontroller and battery, senses the magnetic field and then wirelessly transmits the information to the sink node via a router. For static detection, the magnetic sensor node is located at the center of each parking space. For dynamic detection, two sensor nodes are installed at the center of the road [61].

Since the use of magnetoresistive magnetic sensors for continuous operation inevitably consumes the precious battery power, typically more than 1.5 mA at 3 V, it will hinder the usage of each magnetic sensor node. In contrast, passive low-power optical sensors can detect the shadow cast by cars but are prone to false detections. Recently, the use of optical triggering to wake up a magnetic sensor, namely combining the light dependent resistor and GMR sensor, has been developed for long-term vehicle static detection, which can significantly reduce the current drain to only 5.5 μA [62]. This compact, reliable, low-power sensor node is very useful for intelligent parking service, particularly for PAC of EVs.

In order to avoid any influence on the traffic, the magnetic sensors are preferably located along the roadside, rather than at the center of the road. Recently, an adaptable roadside vehicle dynamic detection system has been developed for various traffic conditions on urban roads. Based on triaxial AMR sensors, a dynamic threshold detection algorithm is proposed for vehicle detection, which can significantly improve the accuracy, reliability and practicability compared with the fixed threshold algorithm. Meanwhile, the vehicle speed is estimated on the basis of the maximum values and the cross correlation of effective parts extracted from two sensor signals [63]. This information is particularly useful for pad-based MAC of EVs because it needs to properly energize the corresponding power pads when the EV is running on the electrified roadway.

6.2. Measurement of Critical Component Parameters

In order to improve the controllability, reliability and safety of EV operation, the critical components such as the battery, electric motor and power converter installed in EVs need to be closely monitored. Since the magnetoresistive magnetic sensors can offer the features of high accuracy, high sensitivity, highly integratable and galvanic isolation, they are being actively developed for measuring the critical component parameters in EVs.

Electric currents including both the DC battery current and AC inverter current are critical parameters that need real-time non-invasive measurements for closed-loop control of electric motor drives in EVs. Particularly, the measurement of AC inverter currents that are composed of a wide spectrum of harmonics is challenging. Recently, the integration of GMR sensors into commercial IGBT power modules has been developed for electric motor drives, which can provide nearly lossless galvanically isolated accurate measurements of AC inverter currents [64]. The IGBT power modules are installed in a 3-phase 5.6-kW inverter induction motor drive, and the GMR-based integrated current sensors are used to support closed-loop field-oriented control that has been widely adopted by EVs.

Temperature measurements including both the battery and power modules are utmost important, which can be used to assess their performances and to trip the protection circuitry for the sake of safety. In particular, the measurement of junction temperature of power modules is very challenging. Recently, a non-invasive high-bandwidth galvanically isolated method has been developed for measuring the junction temperature of power MOSFETs [65]. In essence, GMR-based current sensing is employed to measure the turn-on current transient properties, and the peak value of the gate drive turn-on output current is used to estimate the power MOSFET junction temperature. This technique can readily be extended power IGBTs which are almost exclusively used by EVs.

Existing load monitoring methods for electric motors are generally effective, but suffer from sensitivity problems at low speeds, non-linearity problems at high frequencies, and mostly invasive which may damage the monitored motors. Recently, a state-of-the-art non-invasive load monitoring technique using magnetoresistive magnetic sensors has been developed for electric motors [66]. As shown in Fig. 8, the GMR sensor that is attached outside the machine frame measures the stray flux leaking from the motor, hence providing time-spectrum features for load monitoring. The transient stray flux spectrogram and time information are proved to be more effective than steady-state information, and can also provide an insight into the faults and failures in the motor. This non-invasive load monitoring can significantly improve the reliability of the motor and hence the whole EV.

7. CONCLUSION

In this paper, after introducing the definition, classification, merits and demerits of various EVs, the state-of-the-art electromagnetics research in electric propulsion, hybrid propulsion, wireless charging technologies, EMI and EMC issues, electric flywheel energy storage and magnetic sensory applications have been discussed. For electric propulsion, the development trend of electric motors is identified to be the class of doubly-salient motors such as the stator-PM motors and axial-flux magnetless motors,and the class of vernier motors such as the vernier PM and vernier reluctance motors. For hybrid propulsion, the research trend of electric machine systems is focused on developing gearless brushless EVT systems such as the DR-EVT and MG-EVT to supersede the existing PG-EVT. For wireless charging, both PAC and MAC are being actively developed in which the rail-based MAC technology is promising to fundamentally solve the long-term problems of BEVs. For EMI and EMC issues, both EMI filtering and EMI shielding are being actively investigated in which the human exposure to electromagnetic field during wireless charging attracts much attention. For electric flywheel energy storage, the off-board application to fast charging stations is more promising than the on-board counterpart, and the development trend is on introducing HTS material to the electric machine and magnetic bearing of the off-board FESS. For magnetic sensory applications, the development trend is to make use of magnetoresistive technology for detection of vehicle occupancy and speed as well as for non-invasive measurement of critical component parameters in EVs.

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