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# E-Mobility – Advancements and Challenges

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**ABSTRACT** Mobile platforms cover a broad range of applications from small portable electric devices, drones, and robots to electric transportation, which influence the quality of modern life. The end-to-end energy systems of these platforms are moving toward more electrification. Despite their wide range of power ratings and diverse applications, the electrification of these systems shares several technical requirements. Electrified mobile energy systems have minimal or no access to the power grid, and thus, to achieve long operating time, ultrafast charging or charging during motion as well as advanced battery technologies are needed. Mobile platforms are space-, shape-, and weight-constrained, and therefore, their onboard energy technologies such as the power electronic converters and magnetic components must be compact and lightweight. These systems should also demonstrate improved efficiency and cost-effectiveness compared to traditional designs. This paper discusses some technical challenges that the industry currently faces moving toward more electrification of energy conversion systems in mobile platforms, herein referred to as E-Mobility, and reviews the recent advancements reported in literature.

**INDEX TERMS** Battery technology, fast charging, high-frequency magnetic materials, high-power-density converters, hybridized battery systems, more electric powertrains, wireless charging.

## I. INTRODUCTION

Next-generation mobile platforms, ranging from handheld devices, mobile robots, and drones to automobiles, aircraft, and ships, require small, light, cost-effective, and longer operating energy systems to meet more aggressive mission profiles [1]–[3]. At the same time, most of these mobile platforms are moving toward more electrification, i.e., electrified-mobility (E-Mobility), if not fully there already. E-Mobility, herein, refers to more electrification of energy conversion systems in mobile platforms. E-Mobility opens new opportunities to meet the required energy system objectives, while also presenting new challenges. As an example

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consider automobiles, where internal combustion engine (ICE) based conventional powertrains are being replaced by hybrid-electric and all-electric powertrains in hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and pure electric vehicles (EVs). Electric powertrains emit no pollutants and are more efficient than conventional powertrains. For instance, the well-to-wheel efficiency of EVs is about 60%, whereas ICE vehicles only convert about 20% of the gasoline energy to motion [4]. Moreover, electric powertrains provide better acceleration and require less maintenance than ICE based powertrains. However, the energy density of batteries is about two orders of magnitude lower than that of gasoline, creating major hurdles along the path toward full electrification of mobile platforms. Hybrid solutions have acted as a bridge toward this ultimate vision of
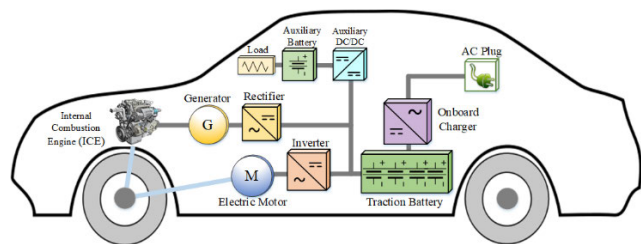
**FIGURE 1.** Powertrain of a typical plug-in hybrid electric vehicle.

E-Mobility. The schematic of the powertrain of a PHEV is shown in Figure 1. Here, the advantages of the high energy density of gasoline are judiciously combined with the advantages of an electrified powertrain to gain overall system advantages. HEVs have been mass-produced since 1997 [5]. EVs are also starting to gain market share more recently, as challenges associated with their operating range, cost, and charging infrastructure are being investigated by researchers. However, substantial work is still required in this area.

Hybrid and all-electric powertrains have also found maritime applications. A scalable diesel-electric hybrid powertrain referred to as the SAVe Line System has recently been introduced [6]. The introduction of batteries in the vessel reduces the generator capacity by 30% and provides load smoothing [6]. For limited periods, the vessel can operate in the battery-alone mode with zero emissions in harbors and sensitive seas such as the Arctic Ocean. All-electric ships are also on the horizon [7]; however, their main challenges are operating range due to limited battery capacity and lack of charging infrastructure.

Large commercial jets are responsible for 11% of all greenhouse gas emissions in the U.S. transportation sector and as such, hybrid and all-electric designs are finding applications in the aviation industry in preparation for the post-oil era [8]. However, there is a significant challenge because the specific energy of jet fuel is 40 times that of the best available battery technology. A hybrid electric airplane E-Fan 1.2 has already been unveiled [9]. Other hybrid aircraft systems are also being developed in operating ranges from 100 – 700 miles with a variety of seating capacity [10]–[12]. Air taxi service is an emerging concept that could also benefit tremendously from E-Mobility due to superior noise characteristics. In addition to the energy storage challenge, the reliability of the energy system is a very important concern in aviation applications.

The design of the energy system of an electrified mobile platform must take into consideration the platform type, its utilization profile, the available sources of energy, and any requirements unique to the application. However, since many mobile platforms share common challenges and have the same needs in terms of a compact, lightweight, low cost, long operating time/range, and reliable energy system, there is much to be gained by combining forces and leveraging advances across these various applications. The objective of this paper is to provide a review of the state-of-the-art

of E-Mobility across these applications, identify the needed research, and provide a resource for researchers developing the next generation of electrified mobile platforms.

## II. BATTERY TECHNOLOGIES FOR E-MOBILITY

All-electric mobile energy platforms are propelled by electric machines powered by rechargeable battery packs through solid-state converters. However, the low energy density of existing battery technologies and high recharging time are some of the main technical challenges toward E-Mobility.

### A. HIGH ENERGY DENSITY BATTERIES

The primary energy source of electric powertrains is made of chemical cells, known as rechargeable battery packs. A rechargeable battery can use different electrolytes and electrode materials to form different types of batteries, with the most relevant configurations being lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), lithium-ion (Li-ion), and lithium-ion polymer (Li-ion polymer) [13], [14].

In ICE vehicles, the lead-acid battery is mainly used for starting and as an auxiliary energy source. The price of a lead-acid battery with 2 V per cell is the lowest among the other types of battery at a specific energy of 30-50 Wh/kg. The two nickel-based battery types, i.e. NiCd and NiMH, with 1.25 V per cell offer the safest battery for mobile technologies with a specific energy of 45-80 Wh/kg for NiCd and 60-120 Wh/kg for NiMH batteries [13]. NiMH batteries have been used in HEVs as an energy source, but are being replaced due to their high self-discharge rate [14]. Li-ion battery with a cell voltage of 3.8 V has a relatively high specific energy, i.e. 100-160 Wh/kg, which along with its higher cell voltage means that fewer cells are required to achieve a particular voltage rating, making the battery pack more lightweight than lead-acid and nickel-based batteries. Therefore, Li-ion batteries are used in many portable electronic devices and EVs [13].

Battery systems generally implement a sophisticated battery management system (BMS) to monitor and control the battery states for safe operations, estimate battery state of charge (SOC) and state of health (SOH) and provide cell balancing. The BMS ensures high performance and longer lifetime by ensuring that operating temperature of battery packs is within specified limits, and the charging and discharging rates of the individual cells are within safety ranges and comply with the battery chemistry limitations [13]–[15]. The BMS also prevents the SOC from exceeding 90% or below 20% to limit high charging and discharging stress on the battery system, which would otherwise degrade battery lifetime [16]. The SOC of batteries cannot be directly measured, and therefore, real-time estimation of the SOC is one of the main tasks of a BMS. The traditional SOC estimation methods consist of the open-circuit voltage method, which is only applicable when the batteries are at rest and the Coulomb counting method, which is highly susceptible to large accumulation of measurement errors due to dis-

turbances [13], [15]. The state-of-the-art SOC estimation algorithms focus on selecting an appropriate battery model and determine the SOC by estimating the parameters of the model [17]–[19]. Another important task of the BMS is to provide cell balancing. Capacity and voltage unbalance between cells in a battery pack are unavoidable due to manufacturing inconsistencies and uneven temperature distribution between the cells. These factors lead to asymmetrical degradation of the cells as they go through more charging and discharging cycles, producing even more cell unbalance with aging [20], [21]. The BMS can balance the cells by either dissipating the excess charge from cells with higher SOCs through passive elements or transistors or move charge between cells using power converters such as DC-DC converters.

## B. SHORTCOMINGS OF CURRENT BATTERY TECHNOLOGY

Investigations are still ongoing in Li-ion battery technology to increase the number of deep charging and discharging cycles. However, Li-ion batteries are reaching their theoretical specific energy limit of 387 Wh/kg [14]. Moreover, the charge and discharge time of Li-ion batteries is not suitable for critical driving instances such as the high rate of current due to energy recovery during regenerative braking, which can accelerate the battery cell aging process [15]. Therefore, new battery technologies need to be developed to achieve a longer driving range. To this end, solid-electrolyte based Li batteries that feature cathodes with liquid or gaseous active materials such as Li-Air and Li-Sulfur technologies and all-solid-state batteries with solid polymer electrolytes are gaining some interest, however, they are still in the research stage [13], [14], [22]. Moreover, cell balancing techniques through the BMS also have some limitations. Cell balancing through charge dissipation is a rather slow process [21] while balancing using DC-DC converters would increase the weight of the battery pack. Lastly, Li-ion batteries are known to have a negative impact on the environment, as they emit $CO_2$ and GHGs during production and disposal. This environmental pollution can be reduced with state-of-the-art recycling techniques, such as hydrometallurgical recovery, pyrometallurgical recovery, and direct recycling [14]. Some of the shortcomings of battery energy storage can be mitigated through hybrid energy storage technologies as discussed in the next section.

## III. HYBRID ENERGY STORAGE SYSTEMS TO REDUCE BATTERY SIZE

Energy storage technologies play a significant role in the rapid growth of mobile energy technologies and have created a new era for hybrid energy storage schemes. Commercially available energy storage technologies are not mature in many aspects. This means the full potential utilization of a specific type of energy storage technology has been yet attained. In fact, despite extensive research for improving different energy storage technologies, achieving a suitable technology that can overcome all the shortcomings of energy storage
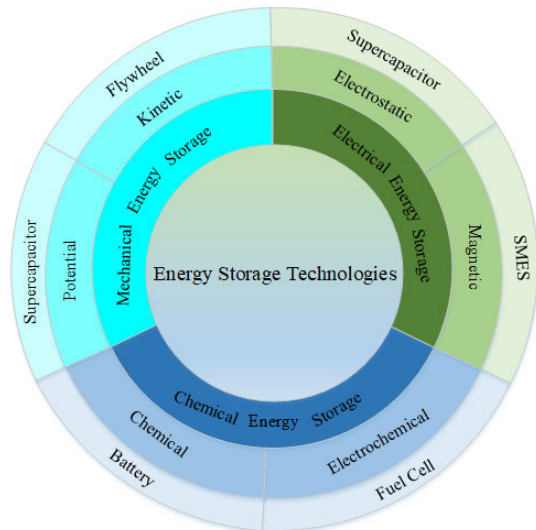


**FIGURE 2.** Energy storage systems technology classifications.

as discussed in the previous section is not expected to be available in the future. Therefore, a potential solution is to adopt a hybrid energy storage system (HESS). Specifically, two or more heterogeneous energy storage technologies are combined to harness each individual energy storage technology's advantage and compensate for their associated drawbacks [23]–[27].

## A. HYBRID ENERGY STORAGE TECHNOLOGIES

The existing energy storage technologies are classified based on the nature of the stored energy (electrical, mechanical, and chemical) in Figure 2. Each technology possesses distinct characteristics that are suitable for different applications [28]. The core properties of some of the energy storage technologies are provided in Table 1. A crucial observation from Table 1 is that the energy storage technologies can be categorized as either high-power storage technologies, defined by a large power density (W/l), or as high-energy storage technologies, represented by a large energy density (Wh/l). High-power storage devices can charge and discharge rapidly, while the high-energy storage devices operate for long durations but with slow dynamics. The high-power storage technologies include superconducting magnetic energy storage (SMES), supercapacitors, and high-power batteries. The high-energy storage technologies are the following: pumped hydro, fuel cells, compressed air energy storage, flywheel, and high-energy batteries. Furthermore, only the battery energy storage system (BESS) is mature enough to be included in both categories. For instance, Lead-Acid, NiCd, Li-ion, and sodium-sulfur (NaS) batteries are considered as high-power storage systems and vanadium redox (VRB) and zinc-bromine (ZnBr) type batteries are categorized as high-energy storage systems. In a HESS, a high-energy storage device is combined with a high-power device. By combining different technologies, a variety of HESS can be theoretically implemented.

**TABLE 1.** Characteristics of energy storage systems [23].

| System | Rating | | Density | | Lifetime | | Self-discharge per day (%) |
|---|---|---|---|---|---|---|---|
| | Power rating (MW) | Typical discharge time | Power density (W/l) | Energy density (Wh/l) | Years | Cycles | |
| Flywheel | 0-0.25 | sec-hr | 5000 | 20-80 | 15-20 | 104-107 | 100 |
| Fuel Cell | 0-50 | sec-24 hr | 0.2-20 | 600 (200 b) | 10-30 | 103-104 | 0 |
| Supercapacitor | 0-0.3 | ms-1 hr | (4-12)×10000 | 10-20 | 4-12 | >500,000 | 20-40 |
| SMES | 0.1-10 | ms-8 sec | 2600 | 6 | - | - | 10-15 |
| Li-ion Battery | 0-0.1 | min-hr | 1300-10000 | 5-100 | | 600-1200 | 0.1-0.3 |
| Lead-Acid Battery | 0-20 | sec-hr | 90-700 | 3-15 | 3-15 | 250-1500 | 0.1-0.3 |

Some investigations have been reported on HESSs for mobile energy technologies such as ship power systems, portable microgrids for disaster events, personal EVs, all-electric aircraft, and public electric buses [29]–[36]. The integration of BESS with SMES [29], BESS with supercapacitors [30]–[33], BESS with hydrogen fuel cells [34], supercapacitors with hydrogen fuel cells [35], and supercapacitors with Redox flow batteries [36] have been studied in the literature as potential HESSs for E-Mobility. Utilizing a BESS/supercapacitor HESS, an improvement in the lifetime of BESS from 5.7 years to 9.2 years has been reported in [31]. The integration of BESS, hydrogen fuel cells and supercapacitors exhibited a faster response to transient power demand, mitigation of stresses on the BESS, and an increase in the efficiency of the energy storage by 8.5% when compared to only a hydrogen fuel cell energy storage system [32], [35]. Life cycle tests performed on a BESS/supercapacitor structure in an EV has demonstrated an increase in BESS lifetime by smoothing the rate of charging and reducing peak currents of the BESS [36]. The supercapacitor can be employed during critical driving instances as a power-buffer. Furthermore, the supercapacitor has been demonstrated to be more suitable to receive the regenerative braking power in urban driving cycles in which the regeneration can be more than 87% of the EV kinetic energy [33], [36]. Therefore, hybrid energy storage technologies can facilitate full electrification of mobile energy systems by enabling energy storage technologies to achieve longer operating cycles, an increased lifetime, and a faster response to transient conditions.

### B. CHALLENGES OF HYBRID ENERGY STORAGE

Considering the aforementioned potential HESS configurations, further investigation is required on flexible hardware and software, i.e. autonomous control, and solutions for these HESS schemes to minimize the energy storage required in mobile systems. These open problems and challenges include: (*i*) maximum utilization of modular DC-sources through advanced switching and control schemes [37], (*ii*) mitigation of pulse-loads and power-surges during transients through supercapacitors, (*iii*) time-coordination and regenerative energy usage through optimal and adaptive control schemes in a single system [38], as well as cyber

coordination between vehicles and vehicles to infrastructures [39], (*iv*) real-time thermal management considerations particularly for battery-based HESS, and (*v*) accurate estimation of life cycle. These approaches will reduce the cost and weight of many hybrid energy systems, including (i) mobile systems and tools, such as EVs, drones, etc., (ii) mobile microgrids for remote areas, and (iii) ships and aircraft with high-power radars, pulsed weapons, etc.

## IV. BATTERY CHARGERS

Chargers are needed to replenish the energy storage devices. Chargers for mobile platforms can be broadly categorized as onboard and off-board chargers. This section discusses the state-of-the-art of both onboard and off-board chargers.

### A. ONBOARD BATTERY CHARGER CIRCUIT TOPOLOGIES

For most PHEV users, an onboard battery charger is a go-to solution for everyday charging. A direct connection to the AC grid provides a universal charging station solution that does not depend on specific battery chemistry or manufacturer. By utilizing a standardized plug, universal charging stations can provide the required AC connection to the onboard charger. North American PHEVs utilize J1772 connector for Level 1 and Level 2 onboard chargers rated at 120V for 1.5kW (with a maximum of 1.9kW for a 20A connection), and 208-240V for 3.3-7.2kW (with a possible maximum of 19.2kW for an 80A connection, NEC 625), respectively [40], [41]. Most onboard chargers offer a rating of 3.3-6.6kW with a 30A connection to a 240V residential wiring.

Currently, the state-of-the-art in onboard chargers is the utilization of a high-frequency (HF) isolation transformer in a resonant topology to provide the required isolation between the vehicle and the grid. This HF topology is often based on either a series LC resonant topology to maximize the efficiency or a phase-shift active-bridge topology as an alternative solution for a wide-range charging operation. The schematic diagrams of the topologies are illustrated in Figure 3. The series LC resonant solution is the most common approach and is equipped with a front-end boost power factor corrector (PFC) converter to interface to the grid [42]–[44]. Researchers have investigated variations of
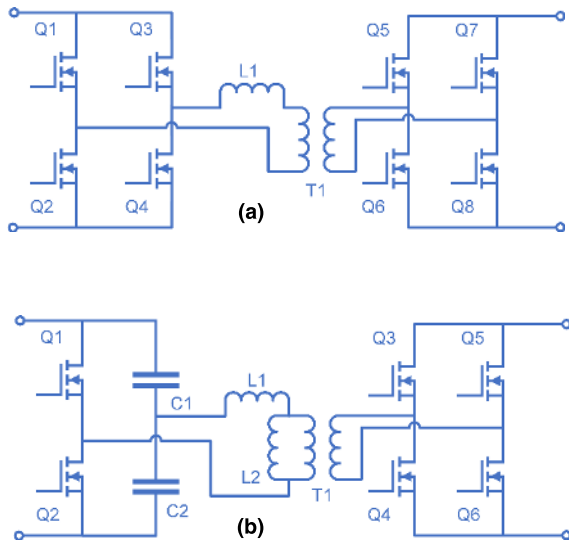
**FIGURE 3.** High-frequency isolation stages commonly used in on-board chargers, (a) phase-shift modulation topology, (b) LC/LLC resonant converters.

this topology to improve specific objectives such as efficiency, cost, and volume. Some of these variations include a resonant LC half-bridge with the front-end PFC and the output buck converters operating in discontinuous conduction mode to reduce the magnetic material requirements [43] and a bidirectional LC resonant converter with a full-bridge front-end interface to support vehicle-to-grid as well as direct-charging from stationary battery banks [44]. Other resonant converters have been investigated to widen the operation range of the charger including an LLC resonant converter [45], LLC with a SEPIC front-end PFC [46], and an LC-LLC bidirectional converter with an interleaved output stage [47]. Phase-shifted dual- and triple-active-bridge (PSDAB and PSTAB) converters have been utilized due to their simpler design and wider operating range. For instance, a PSDAB for the high voltage battery combined with an LLC resonant converter for the 12V battery has been utilized in [48] and [49]. In [50], a PSTAB is incorporated to simultaneously charge both high and low voltage batteries.

The utilization of wide bandgap (WBG) technologies has entered the onboard charger industry to increase the efficiency of these chargers while reducing the size of passive elements [50]. In particular, the commercialization of Gallium Nitride (GaN) and Silicon Carbide (SiC) devices with AEC-Q10x rating has made both technologies suitable for this application. High voltage SiC devices are widely available and have been incorporated in onboard chargers such as an LLC resonant converter [46]. In [49], researchers investigated the utilization of a 6.6kW GaN-based PSTAB to achieve a switching frequency of 200kHz to reduce the size of the HF transformer to a planar solution.

The current onboard charger technologies face several technical challenges and opportunities. Onboard chargers have a low power rating for achieving lightweight designs. However, this leads to long charging times for vehicles.

To maintain lightweight design with faster charging features several new topologies are being considered in the literature. A single-stage isolated PFC has been investigated in [51] to achieve higher efficiencies. The propulsion system of EVs has been repurposed for fast charging with limited additional hardware in [52] and [53]. A nine-phase permanent magnet motor has been proposed in [54] to eliminate non-zero torque production during charging when repurposing the propulsion system as battery chargers. However, these solutions are not commercialized yet. Large-scale penetration of PHEVs and EVs will also increase the peak demand on the grid and in particular in distribution networks, where this demand was not planned [55], [56]. This peak demand for highly penetrated residential neighborhoods is up by a factor of two to four, which can lead to lower power quality and accelerated equipment damage [57]. An opportunity in the area of the onboard charger is the emergence of wireless chargers, which can provide an alternative solution to residential charging. Wireless charging will be discussed in the next section.

### B. FAST-CHARGING STATIONS

Off-board charging through fast-charging stations (FCSs) where the peak demand is planned and managed can be the key to reduce the impact of EVs on the electrical grid. In these solutions, often a solid-state transformer (SST) is incorporated to achieve isolation in a smaller volume and to directly interface the 12.4kV grid [58] while a stationary battery system allows for demand-curve smoothing. For instance, in [59], the feasibility of SST extreme fast chargers from the 12.4kV distribution network is being investigated where the utilization of stationary battery banks is expected to ensure a smooth demand profile. Standards regarding Level 3 AC chargers are also expected to be released in North America. Currently, North American Level 2 chargers are offering to charge at a rating of 6.6kW. This rating can be increased to 19.2kW with an 80A circuit if the connection is supported by the residential transformer [40], [41]. Three-phase Level 2 chargers can have a maximum supported rating of 43kW [60], [61], while a Level 3 charging standard has been developed in Japan for DC chargers [62]. Furthermore, for ultrafast charging in the capacity of several hundred kW, DC chargers have been suggested in recent articles.

On the other hand, Level 3 FCSs are bulky, costly to manufacture, expensive to install, maintain and expand, and are not practical without the evolution of a comprehensive national charging infrastructure [63]. Concomitantly, longer-range EVs with larger and more powerful batteries will require larger charging stations to expedite the charging time. Access to FCSs whose capacities can easily grow with demand such that E-Mobility investment cost is reduced, while the electric fleet fueling is intelligently managed, mandates innovation in modular and scalable power conversion architectures for FCSs along with their energy management strategies. Nevertheless, expansion and deployment of such modular and scalable FCSs for EV fleet charging exacerbate adverse impacts on the utility grid because as the number of stations increases,
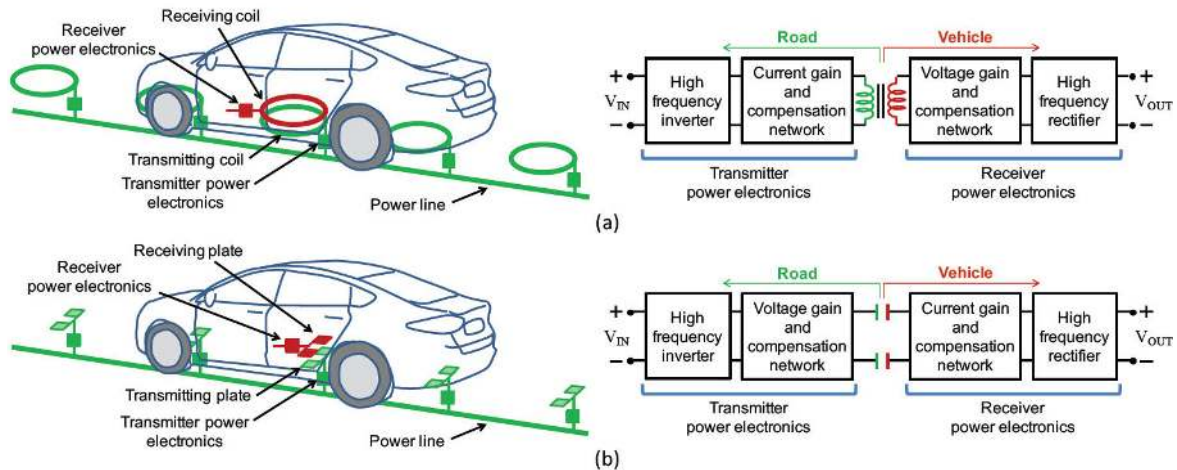
**FIGURE 4.** Physical implementation (left) and block diagram representation (right) of two approaches to deliver energy wirelessly to electric vehicles from an electrified roadway: (a) inductive wireless power transfer (WPT) using coils (embedded in the roadway and in the vehicle) that are coupled through magnetic fields, and (b) capacitive WPT using plates coupled through electric fields.

fleets of vehicles get to charge simultaneously. Expansion of the existing solutions to meet higher demands corresponds to the installation of identical stations [64]–[66], which may not be the most efficient and cost-effective solution. FCS charging architectures with integrated battery storage system which meet the scalability, modularity, efficiency, low cost and at the same time have the flexibility to tap in energy from local distributed generation such as rooftop Photovoltaic (PV) panels, can potentially maximize efficient use of available energy while minimizing the adverse impact on the utility grid.

## V. DYNAMIC WIRELESS CHARGING

An approach to overcome the need for extremely fast charging and the need for heavy and expensive batteries in EVs is to substantially reduce the onboard energy storage and instead deliver power wirelessly to the vehicle while it is in motion. With this battery size reduction, dynamic wireless chargers can reduce up to 20% of the installation cost when compared to stationary chargers [67]. Notice, this cost reduction is valid even after considering the additional road renovation required for dynamic charging. Wireless charging makes autonomous mobile platforms truly autonomous as they can charge without human assistance. In-motion (dynamic) wireless charging also enables less ridesharing autonomous EVs to meet passenger demand, as the vehicles can remain in service for longer.

### A. WIRELESS CHARGING TECHNOLOGIES

Near-field, i.e. nonradiative, wireless power transfer (WPT) systems are of two types: inductive, which uses magnetic field coupling between conducting coils, and capacitive, which uses electric field coupling between conducting plates to transfer energy, as illustrated in Figure 4. For medium-range applications, in which the distance between the transmitter and the receiver couplers is comparable to the size of the couplers, as can be seen in EV charging, inductive WPT systems have traditionally been preferred. Building on the

work accomplished for material handling applications during the 1990s [68], the past decade has seen tremendous progress in inductive WPT technology for stationary charging of EVs [69], [70]. However, for magnetic flux guidance and shielding, inductive WPT systems require ferrite cores, making them more expensive and bulky. Furthermore, to limit losses in the ferrites, the operating frequencies of these systems are kept under 100 kHz, resulting in large coils and low power transfer densities. The higher cost and low power transfer density are particularly problematic for dynamic charging, as these systems need to have high power capability to deliver sufficient energy to the vehicle during its brief time passing over a charging coil. As a result, dynamic inductive charging is yet to become commercially viable, although a few experimental systems have been demonstrated [71]–[73].

Capacitive WPT systems have potential advantages over the inductive systems because it reduces the need for electromagnetic field shielding. Also, because capacitive WPT systems do not use ferrites, they can be operated at higher frequencies, allowing them to potentially be smaller and less expensive. Hence, capacitive WPT could make dynamic EV charging a reality. However, because of the very small capacitance between the road and vehicle conductive plates, effective power transfer can occur only at very high frequencies, making the design of these systems extremely challenging. With the recent availability of wide-bandgap power semiconductor devices that enable higher-frequency operation, high-power medium-range capacitive WPT systems are becoming viable [74]–[78].

### B. WIRELESS CHARGING CHALLENGES

The technology needed to enable effective dynamic charging of EVs is still in its nascent stage. Numerous challenges related to performance, cost, and safety need to be overcome before the vision of wirelessly powered EVs can be realized. Two significant challenges associated with dynamic charging of EVs are: (1) achieving high-power transfer density at high
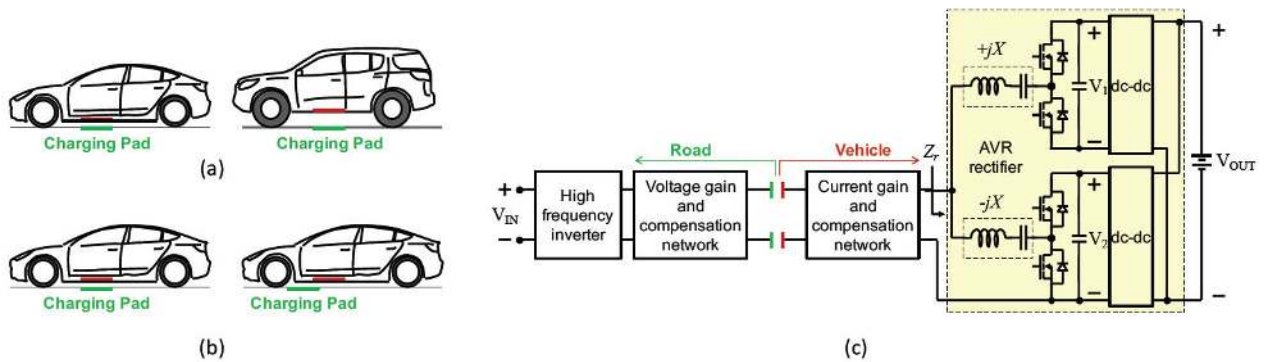
**FIGURE 5.** Coupling variations and an approach to compensate for these variations: (a) variation in coupling due to different vehicle road clearances, (b) variation in coupling due to change in vehicle position as it drives over the charger, and (c) a capacitive wireless power transfer (WPT) system with an active variable reactance (AVR) rectifier that can provide continuously variable compensation by controlling the voltages $V_1$ and $V_2$.

efficiencies while meeting electromagnetic safety requirements, and (2) maintaining effective power transfer even as the couplers' relative position changes.

The size of the couplers in WPT systems can be reduced and the power transfer density increased by designing the systems to operate at higher frequencies. In inductive systems, the increase in induced voltage with higher frequency compensates for the reduced mutual inductance of the smaller coils, and in capacitive systems, the increase in displacement current with higher frequency compensates for the smaller plates' lower capacitance. Higher operating frequencies also enable smaller power electronics associated with WPT systems due to a decrease in energy storage requirements. However, achieving high efficiencies at high switching frequencies is very challenging. Also, the fringing fields of WPT systems must be within safe levels (as defined by the International Commission on Non-Ionizing Radiation Protection [79]) in areas occupied by people and animals, e.g., the vehicle cabin and outside the perimeter of the chassis. These requirements can be met through circuit stages that provide appropriate voltage and current gain as well as reactive compensation (see Figure 4). An active area of research is the design of these circuit stages [80]–[83]. In addition to passive shielding, active techniques to meet electromagnetic field safety requirements are also being explored. These include techniques traditionally used for beamforming in radars and other far-field applications [84]. Near-field phased-array field focusing approaches that use multiple phase-shifted WPT couplers to achieve reductions in fringing fields provide numerous opportunities for innovation [85], [86].

To achieve effective power transfer, WPT systems need to operate close to the resonant frequency of the resonant tank formed by the coupler and the compensating network reactance. However, the coupler reactance depends on the vehicle position, speed and vehicle-road clearance, see Figure 5. Thus, these factors affect the effective power transfer between the transmitting and receiving pads [67]. The drift between resonant and operating frequency causes a reduction

in power transfer and WPT system efficiency. In WPT systems that operate at frequencies below 100 kHz, where bandwidths are not restrictive, the traditional way to deal with variations in coupling is to change the operating frequency to track the resonant frequency [87], [88]. However, in high-frequency WPT systems, the operating frequency must stay within one of the designated, very restrictive industrial, scientific, and medical (ISM) bands (e.g., 6.78 MHz, 13.56 MHz, and 27.12 MHz [89]). One solution, employed in low-power inductive WPT systems, is to use a bank of capacitors that can be switched in and out of the compensating network, to keep the resonant frequency roughly unchanged as the transmitter and receiver move relative to each other [90]. This is not an effective approach for higher-power WPT systems as the switches must be much bigger and more expensive to keep the system efficient. This approach is also less suited to capacitive WPT because it requires multiple switchable compensating inductors, which are bigger than capacitors. Other adaptive impedance matching techniques include the use of saturable and variable inductors [91], and high-frequency rectifier and inverter architectures that compensate for coupling variations while operating at a fixed frequency [92], [93]. These include the active variable reactance (AVR) rectifier shown in Figure 5. By appropriately controlling the output voltages of its two coupled rectifiers, the AVR can provide continuously variable compensation while maintaining optimum soft switching to ensure high efficiency. This compensation architecture ensures that the output power of the WPT system is maintained at a fixed level across wide variations in coupling and is applicable to both capacitive and inductive WPT systems.

High-performance, safe, and cost-effective dynamic EV charging has the potential to revolutionize road transportation. As the first step to its commercial integration, the SAE J4857 standard defines the permissible frequency band, interoperability, and safety to ensure electromagnetic compatibility with other electrical equipment in the car, and safe electromagnetic field human exposure [67]. The combination of capacitive and inductive WPT that will enable
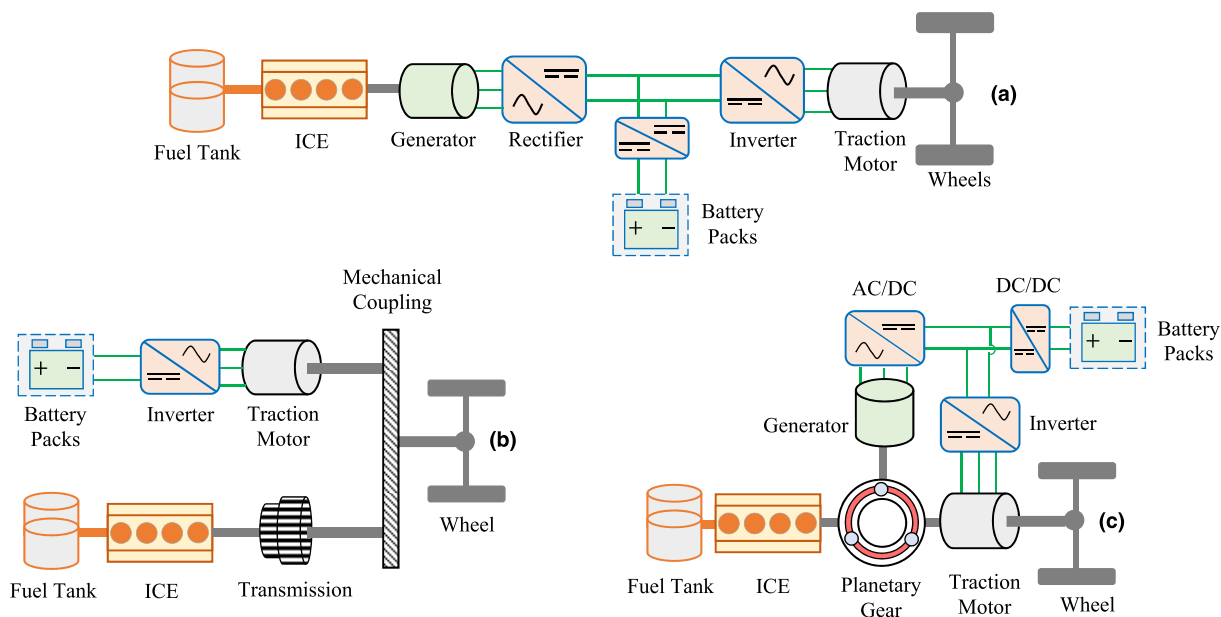
**FIGURE 6.** Schematic diagrams of (a) series hybrid electric, (b) parallel hybrid electric, and (c) series-parallel hybrid powertrains.

this revolution remains an open question, and both systems offer tremendous opportunities for research.

## VI. HIGH-POWER-DENSITY CONVERTERS FOR POWERTRAINS

High-power-density converters are essential for most mobile energy systems. Ships, EVs, and spacecraft are among mobile platforms that require high-power-density converters to increase their mobility and minimize the required power.

### A. POWERTRAIN CONVERTER TECHNOLOGIES

Schematic diagrams of commonly adopted HEV and PHEV powertrains are illustrated in Figure 6 [94]–[97]. In series hybrid powertrains, the ICE engine is mechanically decoupled from the wheels as shown in Figure 6(a), which allows the engine to operate in its high-efficiency region. The overall efficiency of the powertrain can suffer, however, as multiple energy conversion stages exist between mechanical and electrical schemes. For a parallel hybrid powertrain shown in Figure 6(b), the ICE engine does not require an electric energy conversion stage to power the wheels. However, the engine cannot always operate in its most efficient speed and torque region because of the mechanical coupling shown in Figure 6(b). On the other hand, a series-parallel or power-split hybrid powertrain combines the features of series and parallel structures as shown in Figure 6(c). Notice, a series-parallel hybrid powertrain is exposed to vibrations because of a need for an electromechanical coupling system [98]. In the case of full EVs, the powertrain structure would be simpler and would consist of the battery pack, the inverter, and the traction motor connected in series. A three-phase inverter is necessary to interface the three-phase electric machine to the DC energy storage element. The two-level voltage source inverter (VSI) based on IGBT devices is the inverter of choice for traction operations due to their

high efficiency and low cost [94]. Some powertrain architectures employ dual VSIs for traction motor and generator machines [94]. A DC-DC boost converter is also introduced in certain designs between the energy storage element and the inverter [94]–[96]. Since EVs operate in light load conditions for a considerable amount of time, applying a DC-DC converter to vary the DC-bus voltage could be a viable option to ensure efficient operation under light loads. The DC-DC boost converter could also enable independent optimization of the battery storage as the battery output voltage can be set independent of the voltage requirements of the electric machines [95], [96]. However, the inclusion of an additional converter decreases efficiency and increases the size of the system. An impedance-source or Z-source inverter, which employs an impedance network consisting of both inductors and capacitors to couple the power source to main converter circuit, can combine the functionalities of the DC-DC converter and the inverter with a fewer number of switches [95], but it requires larger passive components [95], [96]. Three-level and other multi-level converter topologies are also being considered for EV powertrains. Increasing the converter level could increase the efficiency of powertrains and provide fault-tolerant capabilities [99]–[101]. However, the increased device count and complicated control structures are hindering the breakthrough of such topologies for EV powertrains.

Increasing switching frequency is the most common technique used to minimize the size of passive components, and consequently reducing the volume and weight of powertrains. However, doing so increases switching losses and lowers efficiency. To address this problem, soft-switching techniques have been traditionally used. Second-order and third-order resonant DC-DC converters are among the earliest solutions for minimizing switching losses. These converters have a resonant tank formed by resonating inductors and

capacitors [102], [103]. By extending the principles of the operation of these converters, DC-AC, AC-DC, or multi-phase AC-AC resonant converters may be developed. In resonant converters, the resonant tank resonates continuously, and switches and diodes typically have higher current or voltage ratings compared to their corresponding PWM configurations. Soft-switching universal converters are another category of power converters that are designed to switch at zero current or zero voltage. These converters can be configured as DC-DC, DC-AC, AC-DC, AC-AC, or hybrid power converters, and are excellent candidates for mobile energy systems [104]–[106]. In [107], a compact and efficient universal power converter is proposed for EV application. This single-stage converter can fulfill the task of the inverter, the DC-DC converter, and the onboard battery charger.

Another promising solution for increasing the switching frequency of power converters while maintaining high efficiency is the use of WBG semiconductor devices, such as those made of SiC or GaN. WBG devices offer significant advantages at the device level, including dramatically higher switching frequency, much higher temperature tolerance, and lower switching losses. Another technique for reducing the size of passive components is designing converters such that they operate in discontinuous conduction mode. This results in increasing the peak value of current or voltage.

Bulky low-frequency transformers are an integral part of many power converters. For instance, in a shipboard power system, a low-frequency transformer provides the required galvanic isolation between the generators and motors. Comparing the weights of commercially available adjustable-speed drives and their corresponding transformers shows that in high power systems, the weight of the transformer typically exceeds that of the converter. Therefore, to increase the power density of the system, power converters that utilize high-frequency transformers instead of low-frequency transformers must be employed. In [108], a high-power-density three-phase AC-AC converter with an integrated high-frequency transformer is proposed for the shipboard power systems.

### B. CHALLENGES WITH POWERTRAIN CONVERTER DESIGN

In the previous subsection, several techniques for increasing power density were discussed. These techniques are sometimes challenging and may require additional consideration. For instance, increasing the switching frequency does not always lead to reducing the size of passive components. In power converters that have equal instantaneous input and output power values, e.g. three-phase inverters and three-phase AC-AC converters, the size of passive components is inversely proportional to the switching frequency; thus, increasing the switching frequency and use of WBG semiconductor devices in these converters can help to minimize the size of passive components. There are other applications in which the instantaneous values of input and output power do not match. Among

these systems are DC-to-single phase AC, single-phase AC-to-three-phase AC, and single-phase AC-to-single-phase AC converters. The size of the passive components in such applications depends on the input and/or output frequency, and the switching frequency does not affect the size of these passive components. Given that the input and output frequencies are much smaller than the switching frequency, the size of passive components used in these converters cannot be reduced by using WBG semiconductors or increasing the switching frequency. These applications typically use large passive components to handle the low-frequency harmonic generated due to unequal instantaneous input and output power values. Several methods have been proposed for addressing this challenge [109]–[111], however, most of them require complex control schemes.

Another challenge in using WBG devices and increasing the switching frequency is the electromagnetic interference (EMI) problem, the effect of which can be minimized by proper shielding, careful PCB layout design, and EMI filters. Moreover, decreasing passive components' volume reduces the surface for cooling them, and this can create new concerns in high-power-density converters [112]. Therefore, new cooling techniques must be sought for high-power-density converters used in mobile platforms.

High-efficiency power converters are also required in mobile platforms. Efficiencies higher than 95% can be achieved for power converters, therefore, a further increase in efficiency might seem incremental. However, an increase in efficiency will result in lower heat dissipation, which can lead to the size reduction of the heat-sink and cooling systems. As a result, the power density of powertrains will increase.

## VII. MAGNETIC MATERIALS FOR E-MOBILITY

Magnetic systems such as motors, generators, and actuators are necessary components to animate robots, elevate drones, and propel EVs. Moreover, passive magnetic components are fundamental to power converter performance. In fact, the design of such systems is often the bottleneck to overall system performance, as their usually substantial size and weight reduce the W/kg energy density and compromises the efficiency of applications.

### A. ADVANCEMENT AND CHALLENGES OF MAGNETICS IN E-MOBILITY

As discussed in the previous sections, the power density of onboard power converters can be increased by shifting to WBG devices, since they enable operation under high switching frequencies with recent research activities targeting the MHz range [113]–[116]. Higher frequencies should also theoretically reduce the size of passive components such as inductors and isolating transformers in mobile energy systems. In reality, however, the relationship is less straightforward as high frequencies also lead to higher inductor core and winding losses, and greater impact of parasitic elements on electronic circuit behavior [113]–[116]. Constructing windings using Litz wires can be a solution to reduce winding losses at high frequencies. However, there

are practical limitations as higher frequencies require wire strands with very small diameters, which increases the manufacturing cost and complexity [113]–[116]. Advanced printed circuit board (PCB) manufacturing techniques can also aid the miniaturization of power converters by enabling planar magnetic components [116]. Planar magnetic cores offer a higher surface area to volume ratio than conventional cores, enabling more efficient usage of magnetic materials. The design of planar components is also easy to automate through advanced computer-aided techniques. However, to extract the maximum benefit from planar magnetics new dielectric materials for PCBs are necessary, as the conventional FR4 material requires an increased number of layers to achieve the necessary distance between windings as the number of turns increases [116].

High-frequency operations could also contribute to the size and weight reduction of electric machines. However, the increase in core losses, copper losses, losses in sleeve materials, magnet eddy current losses and also mechanical stress on the machine has to be considered [117], [118]. Electric machines in transportation applications also require operation under variable speeds. Permanent magnet synchronous machines (PMSMs) built using "hard" magnetic materials are usually employed for traction in transportation applications for high torque and power density [119]. Magnetic materials are typically categorized either as "hard" or "permanent" (demonstrating large resistance to magnetic reversal) or "soft" (extreme ease of magnetic reversal). With hard magnetic materials, however, the back electromotive force (EMF) the machines induce could limit high-speed operation. To achieve high-speed operation, flux-weakening control strategies can be used, which applies a negative direct axis current to suppress the magnetic flux at high speeds [119], [120]. However, this increases copper and iron losses due to flux harmonics. To address this problem, variable flux PMSMs (VF-PMSMs) can be utilized that use a combination of hard and soft magnetic materials in either a series or parallel configuration. The magnetic flux in these machines can be adjusted by dynamically changing the magnetization state of the materials. Therefore, both hard and soft magnetic materials are utilized in electric machines, and their resistance to magnetization reversal, the coercivity, may be controlled through the engineering of the structure at the atomic, nanoscopic, and microstructural levels. To date, the main power frequency of standard electric machines ($< 1$ kHz) has permitted incorporation of non-grain-oriented FeSi alloys, i.e. electrical steels, a mature material that exhibits high AC losses and thus low energy transfer efficiency [121]. However, as the losses increase with frequency, research into advanced magnetic materials becomes of paramount importance.

## B. ADVANCEMENT AND CHALLENGES OF NEW MAGNETIC MATERIALS

End users and manufacturers for mobile technologies have expressed the desire for improved hard magnetic materials

with properties that are superior relative to today's state-of-the-art rare-earth-based "super magnet" materials. Stringent operating conditions of mobile energy systems call for higher magnetic induction to allow magnet weight reduction, a smaller reversible coefficient of coercivity to foster stable, higher-temperature operation, and increased durability with a lowered corrosion propensity for improved mechanical and chemical robustness. These engineering considerations are accompanied by persistent economic, source sustainability, and environmental concerns associated with the rare-earth magnets. Potential options for new types of suitable permanent magnets that are free of critical elements include the alnicos, hexagonal oxide ferrites, and chemically ordered FeNi, known as tetrataenite [122]. However, these materials are not yet ready for mobile applications: the alnicos and tetrataenite remain as research materials, and ferrites, by virtue of their low magnetization, requires large volumes of material to generate sufficient flux for machine operation [122].

Regarding soft magnetic materials, the desire for smaller, more powerful and more efficient electrical machines with on-demand rapid torque/rapid current variations requires soft magnetic materials of superior performance at elevated frequencies. Amorphous and nanocrystalline soft magnetic sheets display improved performance relative to the electric steels. These materials still require lamination with insulating polymeric sheets that reduce losses [123] but also dilute the core magnetization, diminishing the available magnetic induction. Furthermore, the sheet geometry of amorphous soft magnetic alloys provides poor magnetic flux alignment, a situation that lowers flux transfer efficiency and tends to degrade with use, particularly at elevated temperature. Insight into new types and forms of soft magnetic materials may be achieved from study of water-quenched amorphous magnetic microwires (diameter 80 – 100 microns) of excellent elevated frequency response (up to 1000 kHz) and superior eddy current insensitivity, accompanied by higher saturation polarization and lower coercivity relative to most current soft magnetic alloys [124], [125]. These wires, comprised of iron, cobalt, silicon, and boron, possess a cylindrical geometry, curved surface topology and reduced, constrained dimension that deliver marked differences in magnetic response from those of analogous sheet or ribbon forms. While the heyday of water-quenched amorphous magnetic microwires occurred in the 1980s and tapered off in the early 1990s [126], a new understanding of amorphous structure and function, new probes and new applications bring this class of materials to the forefront once again.

Magnetic microwires have the potential to revolutionize core design to become three-dimensional (to almost a 'pixel' level), enabling power supply designers to create shapeable, curved, and smaller geometries for inductors and transformers. Next-generation design of transformers and high-frequency power inductors, potentially with unusual geometries, will be conceived that incorporate novel magnetic materials, forms, and topologies to facilitate high-density packaging and high-efficiency performance.

## VIII. CONCLUSION

Mobile platforms such as personal transportation systems, ships, drones, and commercial aircraft are rapidly moving toward the electrification of their energy conversion systems. To accommodate this imminent transition, challenging design and technical requirements need to be met. This paper has identified several pressing issues that these technologies share, elaborated upon their state-of-the-art, suggested potential solutions to such problems, and identified possible research thrusts moving forward. Current Li-ion battery technologies are reaching their theoretical specific energy limits, while new Li-based technologies are still not commercially viable. Transitioning to hybrid energy storage technologies can mitigate some of the Li-ion battery shortcomings by enabling longer operating cycles, increased lifetime, and rapid response to transients. These solutions are envisioned to materialize as more flexible hardware/software, i.e., autonomous control, techniques are developed. In a parallel effort, onboard and wireless chargers are transitioning to fast charging and dynamic wireless charging, respectively. Both technologies are focusing their future development efforts in the design of more compact, cost-effective, and efficient charging systems. In addition to the battery storage and its charger, the onboard converters are adopting newly developed wideband gap semiconductors, control schemes, and converter topologies to increase their power density and operating temperature profile. However, the increase in the power density of the converters must go in hand with the advancements in magnetic materials. Together, the developments in battery energy storage systems, battery chargers, powertrain converters, and magnetic materials constitute the foundation of technological transition areas toward the new generation of E-Mobility.

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