Guest Editorial Special Issue on High-Power Fast Chargers and Wireless Charging

I. Introduction

ELECTRIC transportation systems have made great strides forward in terms of performance and cost-effectiveness. Electric drivetrains provide better efficiency and higher reliability due to the lower complexity and smaller part numbers compared to combustion-based drivetrains. As such, electric transportation concepts are becoming viable for all modes of transportation. This move toward transportation electrification is enabled by the drastic improvements in battery performance, making passenger vehicles with a range of over 200 mi cost-competitive with petroleum-powered vehicles. Despite the increasing number of electric vehicles (EVs) on the roads, the lack of charging infrastructure and long charging times restricts the use of these vehicles for daily commutes and short-distance trips.

To address the problem of limited on-the-vehicle storage capacity, there is a need for a cost-effective and ubiquitous charging infrastructure that can compete with the existing gasoline-powered vehicle-refueling infrastructure. This special issue aims to present recent discoveries and concepts of rapidly delivering power to EVs. Two approaches of particular interest include high-power conductive and inductive (so-called "wireless") charging technologies. This special issue contains 17 articles with original research work and one technology review article. The articles are categorized by their topics in the following.

Extreme Fast Charging

In "Extreme fast charging of electric vehicles: Technology overview," Tu *et al.* considered the most recent advancement in the fast charger technology. This review article looks at the state-of-the-art EV charging infrastructure that will be necessary to support current and future EV refueling needs. The article reviews the status of the EV charging infrastructure showing the trend toward chargers with very high power capability, presents the design considerations of the extreme fast-charging (XFC) stations, and reviews typical converter topologies suitable to deliver XFC. An emerging approach, discussed in detail in the article, is to design XFC stations with medium-voltage solid-state transformers (SSTs) to replace the conventional line-frequency transformers that are connected directly to the medium-voltage distribution line, thus improving the system efficiency and reducing its footprint.

In "Rating a stationary energy storage system within a fast electric vehicle charging station considering user waiting times," Bryden *et al.* proposed a novel method to determine the optimum stationary energy storage capacity at a fast-charging station. They focused on developing a high fidelity model for estimating the EV users' waiting time as a function of the predicted number of EVs that will use the fast-charging station each day, the probability of an EV arriving at the fast-charging station at each hour of the day, the charging time for one EV, and the available grid connection power at the fast-charging station location. The proposed algorithms can then estimate the reduction in the waiting time as a function of the size of the energy storage system at the station.

In "Modeling and control of three-level boost rectifier based medium-voltage solid-state transformer for dc fast charger application," Lee *et al.* presented the modeling, control, and system design of a series-stacked three-level boost (TLB) rectifier for fast chargers that are connected directly to the medium-voltage distribution line. The proposed fast charger system consists of a 16-kW, 3.8-kV$_{rms}$ prototype with four modules configured in an input-series output-parallel configuration, where each module consists of a diode bridge, front-end TLB rectifier, and back-end stacked half-bridge LLC converters. They also presented a novel control approach based on an accurate feedforward control that helps in producing high power quality waveforms to minimize the total harmonic distortion in the current waveform.

In "A drivetrain integrated dc fast charger with buck and boost functionality and simultaneous drive/charge capability," Viana and Lehn proposed an onboard charger that utilizes the traction inverter and motor winding inductance to interface to a dc source. The proposed topology provides buck and boost capabilities for maximum flexibility and enables simultaneous driving and charging, thus making the concept compatible with conductive and inductive dynamic charging.

In "Modeling, design, analysis, and control of a non-isolated universal on-board battery charger for electric transportation," Praneeth and Williamson investigated the nonisolated on-board charging solutions to efficiently charge vehicle batteries with an ac power supply. They show that a two-switch nonisolated converter capable of operating in buck and boost modes provides an efficient and cost-effective solution.

Another important constraint to fast-charging EV batteries is the ability of the lithium-ion chemistry to accept a charge. At extremely cold temperatures, EV battery charge acceptance diminishes to a level where fast charging is not possible.

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An effective way to quickly heat up the batteries is to inject ac currents into the batteries prior to the start of charging. In "Integration of magnified alternating current in battery fast chargers based on dc–dc converters using transformerless resonant filter design," Soares *et al.* proposed exciting the resonance of the output filter of a dc/dc converter to inject ac currents into lithium-ion batteries.

High-Power Wireless Charging

In the area of wireless charging, there is a never-ending aspiration to increase power level, improve efficiency and misalignment tolerance, reduce leakage field, lower the system cost, and reduce the weight of magnetic couplers. In this Special Issue, 13 articles are published that discuss some relevant challenges of high-power wireless power transfer (WPT) and its application in electrified transportation, industrial automation, and so on. Among them, ten articles evaluate inductive wireless charging, one is focused on capacitive systems, one article covers inductive–capacitive hybrid systems, while one article deals with conductive dynamic charging issues. More specifically, the topic of improving magnetic couplers is discussed in four articles, three articles talk about innovative designs of compensation networks, two of them describe new topologies and controls of primary converters, while three of them are focused on dynamic charging systems. A brief overview of all articles is provided in the following.

Even after many years of WPT development, designing better coils is still a very active research area. The quadruple coil structure is more complicated than most traditional polarized and nonpolarized designs, but it may offer some advanced features. These are the questions that Ahmed *et al.* investigate in their article "Design and interoperability analysis for quadruple pad structure for electric vehicle wireless charging application." They developed a model and optimization methodology for a quadruple receiver and conducted an interoperability analysis of the quadruple coil with respect to rectangular, DD, and DDQ structures. Their findings favor quadruple coils in terms of coupling coefficient, coupling interoperability, and misalignment tolerance.

Castillo-Zamora *et al.* have the same motivation in their article "Hexagonal geometry coil for a WPT high power fast charging application," in which they proposed the use of hexagonal coil instead of traditionally used circular or rectangular shapes. The article combines analytical and simulation approaches to develop a coil design methodology. The design is intended to reduce pad weight and maintain high efficiency.

Another critical component of a pad design is the ferrite used to shape the field, and its optimum design is the subject of "Loss minimization design of ferrite core in a DD-coil based high-power wireless charging system for electrical vehicle application" article published by Mohammad *et al.* The majority of pad designs so far employ simplified forms of ferrite structures often determined by the tile- or I-shaped cores available on the market. Due to nonuniform field density through the core, different parts of the ferrite structure generate more loss than others, while the latter may contribute less to the coil quality factor. In the article, they tackled the problem of optimum ferrite design in a nonuniform field environment under a DD WPT coil. They identified a parameter describing the uniformity of the field inside the core and used it to derive the optimum shape. The procedure is tested on a 5-kW DD prototype resulting in 20% of core loss reduction.

Reducing complexity and cost is a long-term challenge in WPT charging systems. In the article "Null-coupled magnetic integration for EV wireless power transfer system," Zhang *et al.* proposed to integrate the inductors from LCC compensation networks with the planar power coils inside the magnetic couplers. They used the system model to study the characteristics of two integrated structures, and they identified the unipolar power coil and a DD compensation coil as an optimum design. The study reveals that the impact of magnetic integration on system currents and active and reactive powers exists, but it can be mitigated through an adequate coil design.

To alleviate the constant current (CC)/constant voltage (CV) charging of EVs, Lu *et al.* proposed a generalized design methodology of a compensation network applicable to both inductive and capacitive wireless charging systems. Their work is presented in the article "Unified load-independent ZPA analysis and design in CC and CV modes of higher-order resonant circuits for WPT systems." For a voltage-fed input and resistive load at the output, they derived resonant conditions that would result in CV or CC mode at the output while still providing zero-phase angle conditions at the input. Using the design guidelines, the researchers built a 3.3-kW prototype, capable of achieving the CV mode at 82 kHz and the CC mode at 90 kHz, with both frequencies being inside the operation frequency window specified by the J2954 standard.

In the article "A coil detection system for dynamic wireless charging of electric vehicle," Patel *et al.* analyzed the problem of vehicle detection in dynamic charging systems in order to attain just-in-time power electronics activation and power transfer. By using magnetic field-based detection, it is possible to improve the reliability and remove the latency time associated with communication-based systems. The proposed system employs a transmitter detection coil integrated with the receiver coil at the vehicle to generate a high-frequency field under the vehicle. Two orthogonal detection coils are installed in the power transmitter pad to measure the high-frequency field and determine the presence of the vehicle. The main features of the proposed topology are low cost, low power consumption, and excellent misalignment tolerance.

Use of the third, auxiliary, coil to which both receiver and transmitter coil are magnetically coupled improves the vertical and lateral misalignment tolerance of WPT systems. However, both the power transfer level and the inverter power factor are still dependent on the position of the receiver and coupling between the coils. In the article "An approach for selecting compensation capacitances in resonance based EV wireless power transfer systems with switched capacitors," Cota *et al.* explored a dynamic way of tuning the resonant auxiliary coils in order to maintain the rated power transfer and an optimum power factor at the inverter output. They proposed a series of switched capacitors to tune two resonant coils and maintain the operation within the split resonant frequency region while misaligned. As a part of experimental validation, they reported a significant increase in the power factor (0.34–0.90) for a 20-cm misalignment between transmitter and receiver coils.

In “Field-oriented control of a three-phase wireless power transfer system transmitter,” Pathmanathan *et al.* explored the way to apply well-known modeling technique of two-pole, three-phase electric machines to a three-phase wireless power system for static charging applications. The known position of the receiver coil allows for a “rotor angle” equivalent to be determined, which leads to the calculation of direct and quadrature axis components of transmitter currents. They used the new current components to calculate the optimum inverter currents and compensation capacitors in order to minimize the system’s copper loss and improve the power factor. To facilitate the operation for large misalignment while maintaining a low power rating of the inverter, they proposed a switched capacitor scheme for two compensation capacitors.

In “Analysis and design of soft-switching active-clamping half-bridge boost inverter for inductive wireless charging applications,” Huynh *et al.* introduced a new inverter to drive a primary side of a WPT system. They proposed the use of a fixed-frequency controlled active-clamping half-bridge boost inverter (HBBI). HBBI operates as a voltage source inverter but requires fewer components than traditional full-bridge structures and demands a low-ripple input current. In the article, they derived a steady-state dc model and focused on the ZVS conditions for efficient operation. They also applied the extended describing function method to derive a small-signal ac model and use it to design a current regulating controller.

Capacitive power transfer (CPT) systems for charging EVs exhibit very low mutual capacitance (pF range), which makes them susceptible to parasitic electrostatic coupling established between the coupler and the car chassis or the ground. The research published in “A new design approach to mitigating the effect of parasitics in capacitive wireless power transfer systems for electric vehicle charging” by Sinha *et al.* is focused on finding a way how to model those parasitics and incorporate them into a design procedure. They further explored a symmetrical compensation structure capable of reducing the coupler model to a traditional four-capacitance structure. The article also presents a measuring methodology to minimize the measuring error of parasitic capacitances. The proposed design is validated on two CPT systems (590 W and 1.2kW), reaching a maximum power density of more than 50 kW/m^2.

In “Evolution of hybrid inductive and capacitive ac links for wireless EV charging—A comparative overview” article, Vincent *et al.* explored the potential of hybridization of power transfer through a combination of inductive and capacitive systems. The article starts with a separate overview and comparison of indicative and capacitive charging systems, trying to identify the potential of hybrid systems and their main challenges. The authors identified and commented on the dependent and independent two-channel hybrid structures operated at high and medium signal frequencies. By combining the merits of IPT and CPT, they expect to reduce the number of components used, increase power density, improve misalignment tolerance and compatibility, and allow power scalability.

The article “Thermal modeling and analysis of an alternating short-segmented conductive ERS” diversifies the dynamic charging methods by introducing the concept of conductive dynamic charging. Abrahamsson *et al.* proposed short segments embedded in the road and connected to a vehicle through a current collector (pickup) device to charge the vehicle batteries. Striving to design a system that can operate in both static and dynamic environments, they identified the localized losses and temperature rise at the charging point as main issues. Through the article, the focus is on the development and validation of a thermal model of a short contact segment as a prerequisite for subsequent structural optimization. The model is implemented in FEM software and validated through outdoor tests on a 1-m segment conducted at Örtofta, Sweden. Based on the results, critical thermal parameters are identified, and some practical suggestions for heat relaxation are provided.

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