Enabling Extreme Fast Charging Technology for Electric Vehicles

As a significant part of the next-generation smart grid, electric vehicles (EVs) are essential for most countries to achieve energy independence, secure energy supply, and alleviate the pressure on environmental protection and energy security. Although EVs have grown rapidly, the slow recharge time is still the biggest obstacle to a wider application. While gasoline vehicles can pump enough gasoline in less than ten minutes, which can carry themselves a few hundred miles. However, most of today's fast-charging techniques take half an hour only to provide very limited miles of electric driving range.

The industry is addressing the slow recharging issue for EVs by increasing the rate of charging to 350 kW and above, known as extreme fast charging (XFC), which allows EVs' recharge time equivalent to refueling gasoline vehicles. Although XFC can help overcome practical EV driving range limitations, the technology also introduces a series of new challenges, which requires an intelligent control for a different power train architecture and components from the current EV offerings.

The aim of this Special Issue is twofold: (i) to capitalize on the state-of-the-art technologies to explore the applicable studies for the fast charging of EVs, in order to address the vulnerability and profit without any compromise on reliability and quality in either realm, and (ii) to actively promote the application of XFC solution for EVs highly recognized by the industry, by only publishing papers which deal with practical consideration instead of purely theoretical works. This Special Issue aims to promote the deep researches related to EVs from experts in various scientific disciplines.

In this Special Issue, the XFC-capable EVs are motivated to address the technology gap in view of battery, high-voltage system architecture, power electronics design, infrastructures, cyber-physical system security and stability issues to the power grid, which provides the unique bridge for an interdisciplinary research cross the XFC technology, and the security and stability of transportation electrification systems.

In order to deal with the operation and market participation problem for EV fast-charging stations (CSs), Duan *et al.* propose the bidding strategies in both energy and reserve markets for an aggregator of multiple fast CSs with energy storage systems. The conditional value at risk-based mixed-integer quadratic programming formulation is built to hedge the risks of random charging demands and volatile market prices. The proposed formulation is converted into a mixed-integer linear programming problem and an iterative solution method is further designed to reduce the computation time. The case studies based on the trajectory data of taxis in Beijing have been carried out. The simulation results show that the aggregator can achieve higher economic benefits while satisfying the fast charging demand of EVs using the proposed method.

Mao *et al.* propose a graph-computing-based integrated location planning model, which maximizes PEV charging convenience while ensuring the power grid's reliability. In addition, the proposed model captures the long-term costs of critical grid assets induced by uncertainty and impulsiveness of charging demand. The model can be easily scaled to various coupling configurations and temporal resolutions through a graph-based scheme. The proposed model is cast as a multiobjective mixed-integer problem and is solved by the cross-entropy optimization algorithm in which the computational efficiency is significantly improved with graph parallel computing techniques.

Shao *et al.* analyze both energy and power demands of the XFC EV CSs. A coordinated planning method for power distribution networks and XFC EV CSs is proposed. The coordinated planning model is developed to satisfy the time-varying and intermittent XFC loads. The on-site batteries are introduced to flatten the XFC energy used and buffer the instantaneous power peaks. The necessity of the power constraints and the role of batteries are discussed.

Sun *et al.* focus on the charging scheduling of on-the-move EVs in a transportation network to minimize EVs' charging latency, including driving time to CSs, wait time, and charging time. The charging scheduling problem is formulated as a graphical game to characterize the strong couplings of charging latency among neighboring EV players. The correlated equilibrium is investigated to describe the joint strategies of EV players, which is expected to further reduce the charging latency of EVs compared with Nash equilibrium. In addition, a method of wait time prediction is proposed by combining the data of deterministic EV arrivals and the stochastic property of potential EV arrivals. The simulation studies show that the proposed method has apparent advantages in situations where the locations of EV players are in dense manners.

Yu *et al.* focus on the EV public charging market with heterogeneous CSs under the time-based billing model. A hierarchical game is proposed to jointly consider the problems of the charging time optimization for EVs, the EV-CS pairing, and the pricing mechanism for CSs. The simulation results show that the proposed schemes can achieve the performance improvement of the charging system.

One of the major barriers for a wider deployment of EVs is the availability of XFC stations. A possible solution is to build a fast-charging sharing system, by encouraging small business

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owners or even householders to install and share their fast charging devices and by reselling electricity energy sourced from traditional utility companies or their own solar grid. To incentivize such a system, a smart dynamic pricing scheme is needed to facilitate those growing markets with fast CSs. The pricing scheme is expected to take into account the dynamics intertwined with pricing, demand, and environment factors, in an effort to maximize the long-term profit with the optimal price. To this end, Fang *et al.* formulate the problem of dynamic pricing for XFC as a Markov decision process and develop algorithmic solutions for different scenarios. Experimental studies are conducted and provide interesting insights.

Zhang *et al.* propose an effective charging planning system for EV to help drivers reduce the total charging time of EVs and recommend the available CS closest to the driving destination. The scheduling problem of EVs charging is formalized as a Markov Decision Process and a deep reinforcement learning-based scheduling algorithm is proposed to address it. The objective of the proposed algorithms is to minimize the total charging time and select the closest CSs to the driving destination of EVs. The experimental results show that the proposed algorithms can significantly reduce the charging time of EVs and be as close as possible to the destination of EVs.

Li *et al.* propose an approach to detecting anomalies in real vehicle power supply systems based on multihead attentions that take the inherent correlations of traffic generated by power-related Industrial Control Systems (ICSs) into account. The experiments are conducted in two real-world power ICS testbeds. Comprehensive experimental results demonstrate the effectiveness of the detection model.

Zhou *et al.* model the EV fast-charging problem as an optimization coordination problem subject to the coupled feeder capacity constraints in the distribution network. A decentralized hierarchical algorithm based on the alternating direction method of multipliers method is designed to solve the constrained coordination problem with its convergence and optimality guaranteed, and a receding horizon-based algorithm is proposed to mitigate the effects of uncertainty over the base demand profiles and the EV populations.

Data like real-time traffic situation and charge point occupation in EV charging networks have significant real-time characteristics. In the paper, Wu *et al.* adopt a distributed storage system, an effective technology to ensure reliable sharing of dynamic data to storage allocation for delay-sensitive data. In order to improve the recovery probability of delay-sensitive data within its timeliness, they establish an access queuing delay model based on the characteristics of sensitive data. Then, they find the optimal storage allocation strategy across distributed storage nodes for data with different delay threshold in terms of the recovery probability.

To achieve the configurable charging profile of battery required efficiently, Wang *et al.* systematically proposed a method to derive effective hybrid inductive power transfer (IPT) converters combating the constraints of loosely coupled transformer parameters, while maintaining nearly unity power factor and soft switching of power switches simultaneously. Starting from some existing topologies having the configurable constant current or constant voltage output, the IPT converter cascades a general T network for mode transition. Design principles with fewer mode switches and compensation components are discussed in detail. The design method can be extended to derive other hybrid converters for onboard EV charging.

In order to improve the power density and efficiency and reduce the cost of the wireless EV charging system, a unified resonant tuning configuration with minimum passive component counts is proposed by Lu *et al.* to achieve constant current and constant voltage outputs at two zero phase angle operating frequencies. According to the proposed configuration, all the possible inductive power transfer and capacitive power transfer topologies are analogized.

Due to the requirements of high power/torque density and the poor working conditions of wheel traction motors used in EVs, severe inter-turn short circuit faults (ITSC) are more prone to occur. Zhao *et al.* study the ITSC characteristics of a permanent magnet synchronous machine (PMSM) used for wheel traction motors in EVs. The influence of fault intensity on machine's parameters and performance are studied at different fault resistances through a finite element method. In addition, factors that affect the amplitude of short circuit current are researched by mathematical formula and simulation, including load state, rotation speed, fault position, and branch inductance. Then, the loss and thermal characteristics of the PMSM under different conditions are analyzed. Experiments are conducted to validate the simulation results.

Apart from the charging technology itself, the battery characteristics of EVs must be specifically taken into consideration to undertake the extremely large current capacity. Jiang *et al.* present a variable-current charging strategy of Li-ion batteries. Since the battery characteristics vary with the state of charge (SoC), it is more reasonable to divide the charging process based on SoC than on cutoff voltage. They find an optimal charging pattern of the proposed strategy by nondominated sorting genetic algorithm-III. The second-order Thevenin model of battery is established to simulate the charging process. Verification experiments are performed and results show that the obtained charging pattern has a temperature and loss reduction of $2.9°C$ and 0.5% compared with constant current-constant voltage strategy under the same charging time and capacity.

With the development of EVs, batteries are usually used as modules. Most models treat the parameters of the battery cells as consistent. This simplification ignores the inconsistencies between the batteries and cannot accurately describe the differences within the battery pack. Fan *et al.* propose a battery pack simplification algorithm based on an equivalent circuit model which is suitable for the rapid simulation of any complex topology battery pack. Relying on the simplified algorithm, under the assumption that the battery parameters conform to the normal distribution, this paper studies the influence of circuit topology, the battery parameter distribution, and the battery parameter correlation on the current distribution through Monte Carlo simulation.

Ruan *et al.* propose an electrochemical model-based quantitative analysis method to uncover the dominant reason for performance decrease and fast-charging limitation of lithium-ion batteries at low temperatures, which helps optimize battery design and develop fast-charging methods. The highly important dynamic parameters are carefully identified by the experimental data and genetic algorithm, thus developing an electrochemical model with high accuracy. The quantitative analysis indicates that the sluggish electrode diffusion is the principal reason for battery available capacity loss. Battery available power attenuation is primarily attributed to the increased film resistance of an anode and the reduced exchange current density of a cathode. The increased film resistance of the anode is responsible for the predominant limitation of low-temperature fast-charging. This quantitative revelation breaks through the traditional understanding from the qualitative analysis that battery performance decreases and fast-charging limitations are highly associated with the most temperature sensitivity parameters.

With the development of XFC technology, CSs need to use energy storage stations to reduce the rising peak to average power ratio. However, a full discharge or charge results in a high-temperature rise, and the electrical model parameters near a specific temperature point cannot be accurately obtained. The short current pulses cannot stabilize the polarization. In the paper, based on an improved Butler–Volmer-Equation-Based electrical model, Li *et al.* use a high-accuracy parameter identification method to summarize the phenomena caused by the rate of change of high-energy LIC. The accuracy of the method is tested under the dynamic stress condition test. The maximum voltage error is less than 2%. Energy efficiency calculation based on the used model is simulated by the design condition from the energy storage station of the Haizhu line in Guangzhou. The maximum error is less than 0.2%.

Sun *et al.* propose a method for identifying the second-order resistor–capacitor equivalent circuit parameters of lithium-ion battery by applying continuous short-time scale pulses and extracting four feature points in each cycle, where the balance is considered between required data and model accuracy. It is illustrated that the proposed method is feasible for different kinds of excitation. At the same time, the applicability analysis of power profiles for different identification methods was carried out. Compared with the conventional method, the proposed method can reduce the average voltage error and the maximum error under the power profile of a dynamic stress test.

This Special Issue has a highly selective review process, in order to comply with the high-quality standards of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS.

The authors, the Guest Editors, are thankful to all the authors who submitted their fine works to this Special Section. Their valuable works are evidence of the dynamism and excellence enlivening this research area. The authors would like to express their sincere gratitude to all the reviewers for providing many valuable comments and for insights into making difficult decisions on this Special Issue's contents.

The authors would like to close by recognizing the help, support, and guidance provided by the Editor-in-Chief Prof. Azim Eskandarian. Thanks also go to Mrs. Miriam Snyder for her professional support and assistance during the whole preparation of this special issue.

The authors hope that the readers will enjoy the carefully picked papers and that this Special Issue will contribute to facilitating further research in this significant area.

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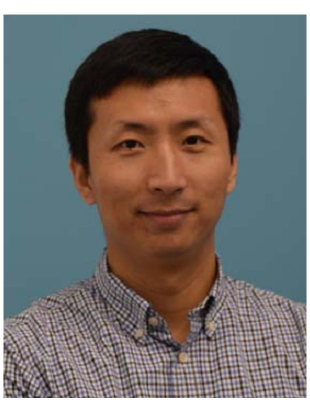

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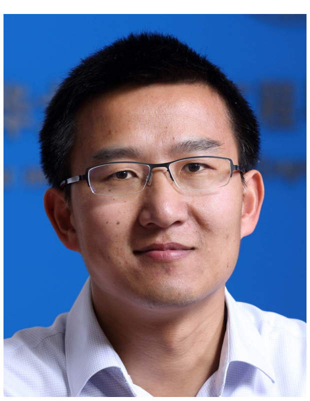

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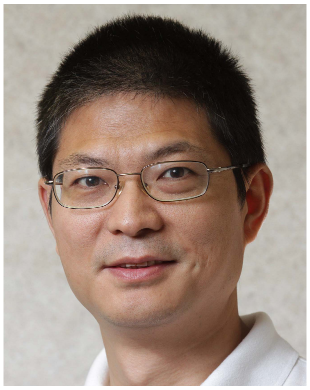

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