Key Technologies and Prospects for Electric Vehicles Within Emerging Power Systems: Insights from Five Aspects

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***Abstract*—The energy revolution requires coordination in energy consumption, supply, storage and institutional systems. Renewable energy generation technologies, along with their associated costs, are already fully equipped for large-scale promotion. However, energy storage remains a bottleneck, and solutions are needed through the use of electric vehicles, which traditionally play the role of energy consumption in power systems. To clarify the key technologies and institutions that support EVs as terminals for energy use, storage, and feedback, the CSEE JPES forum assembled renowned experts and scholars in relevant fields to deliver keynote reports and engage in discussions on topics such as vehicle–grid integration technology, advanced solid-state battery technology, high-performance electric motor technology, and institutional innovation in the industry chain. These experts also provided prospects for energy storage and utilization technologies capable of decarbonizing new power systems.**

***Index Terms*—Electric vehicles, engineering philosophy, high-power density motor, new power system, solid state batteries, vehicle grid integration.**

I. Introduction

IN order to fully clarify technical status and development trends of using electric vehicles (EVs) as energy storage units in emerging power systems, a comprehensive review and discuss on energy and power system technology of EVs is essential. Therefore, CSEE JPES held a forum on the key technologies and prospects for EVs within emerging power systems, which brought together experts and scholars in this fields to share their viewpoints on the trends of distributed EVs as energy storage devices, next generation battery technology, advanced motor technology, vehicle to grid technology, and engineering philosophy of EVs. This work shows key academic viewpoints in the forum. In Section II, Professor Ouyang explores the necessity, potential, and technical frame of EVs as distributed energy storage units in a power system. In Section III, Professor Sun introduces technical routes to realize solid-state batteries with a halide electrolyte. In Section IV, Professor Cai illustrates the technological frontiers and challenges of an advanced motor and propulsion system. In Section V, Professor Song presents the key technology to solve the uncertainty of vehicle to grid. In Section VI Professor Chan discusses engineering philosophy and cultivate scientific spirit in development of EVs. In the conclusion of this paper, Section VII summarizes the main viewpoints of the experts.

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II. Professor Ouyang: EVs and New Power Systems—Prospects of Vehicle–grid Integration Technology

China has the world's largest installed capacity for new energy power generation, yet the volatility of this energy source remains a concern. Simultaneously, the burgeoning growth of new energy vehicles, particularly in supercharging, poses challenges to grid stability. An urgent need emerges for an innovative power system centered around energy storage, notably highlighting the growing attention on batteries.

Against this background, the key solution lies in vehicle-to-grid (V2G) utilization to address both grid stability and charging capacity concerns. EVs, when parked and connected to the power grid via bidirectional charging piles, enable peak shaving. This synergy, fostered by governmental, corporate, and user involvement, positions EVs as catalysts for energy trading, promising substantial economic benefits for all stakeholders.

Furthermore, the realm of energy storage has witnessed a paradigm shift through V2G storage—a cost-effective, secure form of distributed energy storage. Forecasts project extraordinary potential by 2040, with an estimated 300 million electric cars collectively exceeding 20 billion kWh capacity, equivalent to China's daily electricity consumption [1].

In this context, an in-depth exploration of V2G applications and technological frameworks was unveiled. EVs can meticulously align with low-voltage distribution networks, such as residential zones, and medium-voltage distribution networks, such as urban highway charging stations.

A technology platform integrates power equipment (such as PVs and wind generators), communication infrastructure, and gateway systems. This integration fosters various functionalities encompassing energy management, load aggregation, energy trading, market services, and predictive travel and load forecasting tailored for EVs.

Expanding on this narrative, research on optimized control for full-band frequency is necessary for the V2G system (see Fig. 1). Regarding high-frequency power grid stability control, virtual synchronous machines, droop-based inertia control methods, and active and reactive power decoupling control methods were introduced [2]. For high to mid-frequency microgrid power distribution and energy management, a method using voltage signals to reflect internal energy balance while simplifying control and communication complexity, thereby achieving synchronized operation between energy sources and loads, was presented. In addition, in optimizing mid-frequency power battery management, an interactive control method aimed at economic optimization based on thermoelectric coupling models and power market mechanisms was introduced [3]. Finally, for low-frequency aggregation and optimal scheduling of virtual power plants, the security boundary of the power grid was considered, and EV behavior prediction was combined to realize high efficiency and economy of charging system configuration [4] and scheduling aggregation.

In this exploration, the multifaceted challenges and potential solutions for developing V2G and superfast charging must be addressed. This V2G system necessitates meticulous coordination among the subjects of interest. A possible mode is for city governments to lead and promote V2G to solve power supply problems, develop new energy, and popularize EVs. Fast charging technology has a high technology threshold in battery and grid technologies [5]–[7]. Possible models include self-establishment charging infrastructures by main manufacturers, with open protocols for small-scale companies.

III. Professor Sun: Advancements and Challenges in Novel Halide Solid-state Batteries

Conventional lithium-ion batteries (LIBs) have transformed the portable electronics industry and are extensively integrated into daily life. However, increasing adoption of LIBs has raised concerns about their physicochemical energy density limit and potential safety risks associated with flammable organic liquid electrolytes. All-solid-state lithium batteries (ASSLBs), employing solid-state electrolytes (SSEs) instead of combustible liquid electrolytes, not only ensure enhanced safety but also hold promise for achieving high-energy density. These batteries, operational across a broad temperature range, are widely recognized as the most promising next-generation energy storage solution and have attracted considerable attention. Remarkable advancements have been made in halide solid-state electrolytes, drawing substantial attention for their application in ASSLBs. These electrolytes exhibit high ionic conductivity at room temperature, wide electrochemical win-

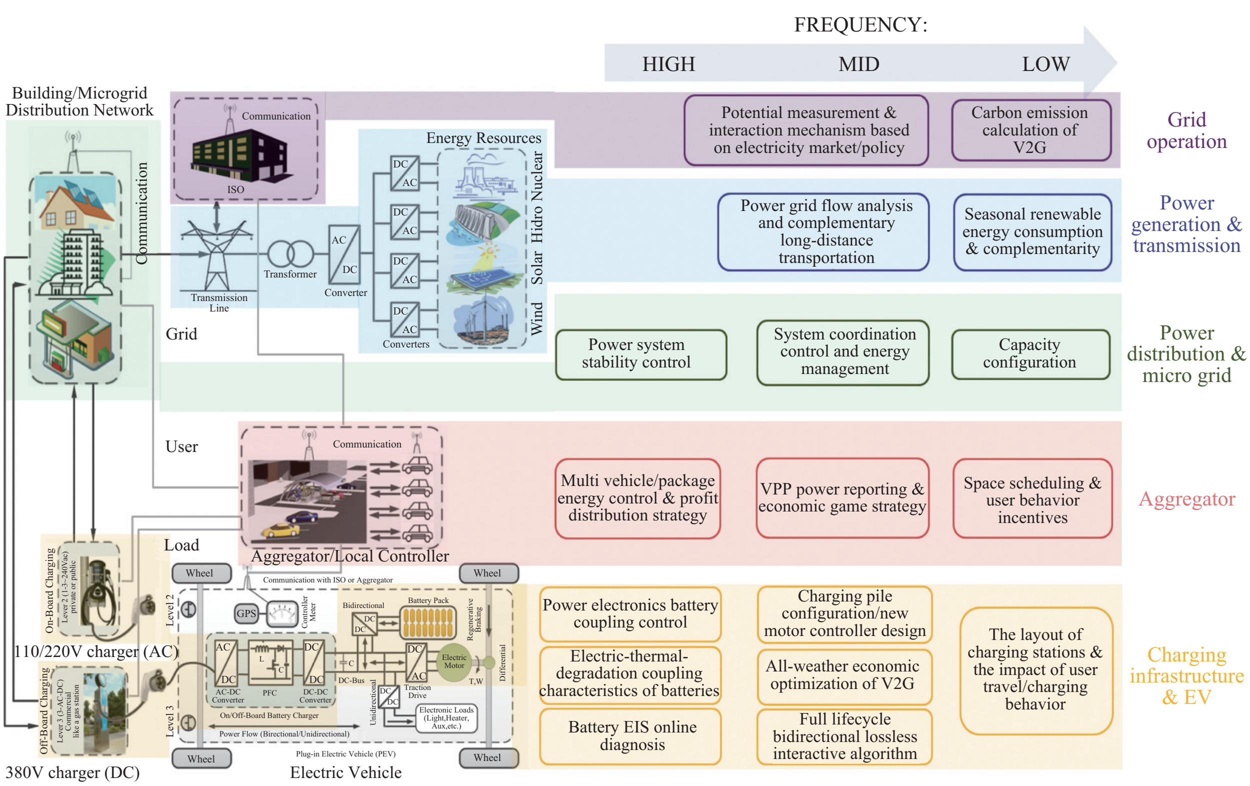

Fig. 1. Research on optimized control for the full-band frequency of the V2G system.

dows, and excellent compatibility with oxide cathode materials. Academician Sun provided a comprehensive exposition on the historical development of halide solid-state electrolytes. Subsequently, a detailed presentation regarding current challenges faced by ASSLBs was delved into, focusing on material concerns, interface challenges, and engineering issues [8], [9].

In halide solid-state electrolyte synthesis, various routes have been explored, with liquid-phase synthesis emerging as particularly promising [10]. This method holds significant potential for advancing halide SSEs because of its unique characteristics and cost-effectiveness. In addition, efforts are directed towards enhancing physical and chemical properties of halide SSEs through strategies such as structural design, simulation calculations, and innovative synthesis [11], [12]. These endeavors aim to ensure compatibility with high voltages, guaranteeing chemical and electrochemical stability in crucial aspects like thermal stability, resilience to air/humidity, compatibility with cathodes/anodes, and intrinsic electrochemical stability windows. Utilizing thin film techniques like ALD/MLD interfacial coating design and in-situ characterization (e.g., in-situ XAS, Raman, XRD), researchers have explored interface mechanisms involving ion and electron transport between halide SSEs and cathode/anode [13]. They found halide solid-state electrolytes show better moisture stability than sulfides and perform higher oxidation limit & cathode compatibility than sulfide counterparts. Achieving practical applications of halide solid-state electrolytes in energy storage presents a multitude of challenges. The primary concern in scaling up solid-state battery production is addressing the large-scale manufacturing of solid electrolyte materials. Additionally, leveraging highly promising dry method fabrication technology for producing ultra-thin inorganic solid electrolyte films and the application of dry electrode techniques are crucial. Expectation is adoption of dry electrode technology will not only be advantageous for the preparation of solid-state batteries but also significantly reduce overall production costs of the all-solid-state batteries [14]. Overcoming these challenges will establish the foundation for the practical application of halide solid-state electrolytes in ASSLBs, offering more promising solutions for future energy storage (see Fig. 2).

IV. Professor Cai: Product Innovation, Technological Frontiers, and Challenges to the Industry Chain in Electric Propulsion Systems

The electric drive system industry chain comprises propulsion motors, power electronic controllers, reduction/transmission gearboxes and key components/devices and materials. In recent years, significant progress has been made and self-reliance capability has been improved in China in electric drive systems, assemblies, power modules and materials. Currently, domestic electric drive assemblies are prevalent, in which the domestic insulate-gate bipolar transistor (IGBT) chips and power modules have market share of over 50%. However, the silicon carbide (SiC) and microcontroller unit chips etc., are still have a domestic production rate of less than 8%.

Compared among advanced motor technologies globally, China still faces a gap of leading motor research and manufacturer in high-end motor technology. The goal of a motor power density of 50 kW/L, set by the U.S. Department of Energy, has been achieved by NC State University, in which a surface-mounted permanent magnet rotor and centralized stator windings with carbon nanotube superconducting copper. Motor prototypes have been built and tested. The electric powertrain product, with power of 500 kW and mass of only 74 kg [15], has been presented by Peter Rowlinson at Lucid Air Motors. New topologies and design innovations were introduced, such as the sintered and bonded permanent magnets with a dual V arrangement, flat wire wave-windings, planetary gears, and oil cooling, with cooling channels arranged at the roots of the winding iron core and, so on. The motors effective power density of 15.65 kW/kg [16] and the entire electric powertrain (including motor, controller, and reducer) density of 6.76 kW/kg have been achieved. In comparison, domestic

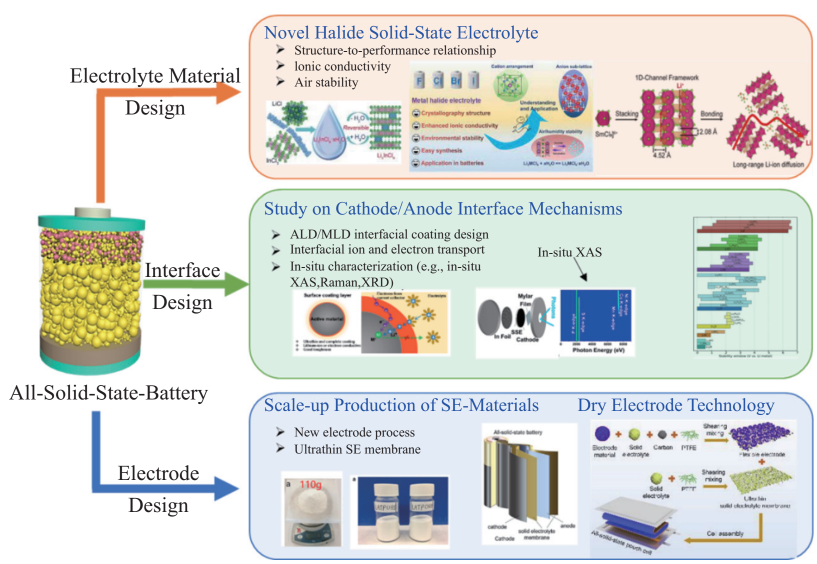

Fig. 2. Summary and outlook on key materials and battery technology for all-solid-state batteries.

motor technology and performance are still far behind. Effective power density of 12 kW/kg at 15 seconds is reached by Chinese OEM, Aion of Guangzhou Automobile Group Co. Ltd., while the mass-produced motor effective material power density ranges from 4.5 to 7 kW/kg by Chinese OEMs and suppliers.

Development trends and technological paths in the electric drive industry are presented in Fig. 3. To electric powertrains for new energy vehicles below Class A characterized by low power and low voltage, strand round wire distributed windings, silicon-based semiconductors, water indirect cooling for heat dissipation, and single-stage reduction gear technologies can be employed. As voltage and power increase, vehicles electric powertrains for above Class B, the technologies will be gradually transitioned to the use of flat wire motors, SiC semiconductor modules, oil direct cooling or oil direct-combined with indirect-water cooling for heat dissipation, and multi-stage gear reductor or multi-speed transmissions.

The main trends in the advancement of electric motors are power density and efficiency increase, which aims to reduce high efficiency motor size. Torque reduction and speed elevation are necessary to achieve this. An insufficient switching frequency of power devices can trigger issues, such as non-sinusoidal currents and acoustic noise. Therefore, increasing motor speed requires elevating the motor controller's switching frequency. Adopting third-generation wide-bandgap semiconductors is a crucial pathway, as the efficiency and temperature resistance can be enhanced. Matching a gear reducer to adapt to the wheel speed is also essential. Overcoming the heat dissipation bottleneck is crucial for achieving high-power-density motors, which consists of optimizing heat dissipation performance, minimizing pump power consumption, and ensuring system strength. Finally, increasing the controller's switching frequency also requires attention to insulation issues.

In the current structure of permanent magnet motors, the rotor primarily incorporates interior permanent magnets (IPM) arranged in configurations, such as double-V and triangular arrangements, since motor torque can be increased from reluctance torque through inductance difference between Q-axis and D-axis. However, as the rotational speed increases to over 20,000 rpm, emergence of advantages in surface-mounted permanent magnet (SPM) motors, since thicker magnetic bridges to meet structural strength will cause high rotor flux leakage of high speed IPM motors. Recently, the SPM topology is initiated by all project developers of Department of Energy of America. The Halbach array arrangement of these permanent magnets is introduced, which contributes to a more sinusoidal distribution of an airgap magnetic field with low harmonic distortion and noise. Notably, concentrated windings should be coordinated with implementing the SPMs.

In the winding innovation field, Professor Cai proposed high voltage "hairpin" flat wire winding technology [17], which has become a technological mainstream for high efficiency propulsion motors. High slot-filled factor, high efficiency, high power density, and low mass etc., are achieved through his invented flat wire winding technology. However, eddy current losses will become higher with frequency or speed and result in relatively high overall AC resistance losses if the thickness of the flat wires in slots increases in slots. Although AC resistance losses could be reduced through increasing layer number of flat wires in the slot, the loss in each flat wire varies with its position in s slot. For instance, higher AC resistance and greater thermal issues exist in the flat wire near slot opening, and the situation is much better in the flat wire at slot bottom, which especially mismatches with the cooling passage structure for water cooling system. End-turn transitioned multi-strands flat wire and the variable thickness flat wires are combined with the stepped slot width, which is

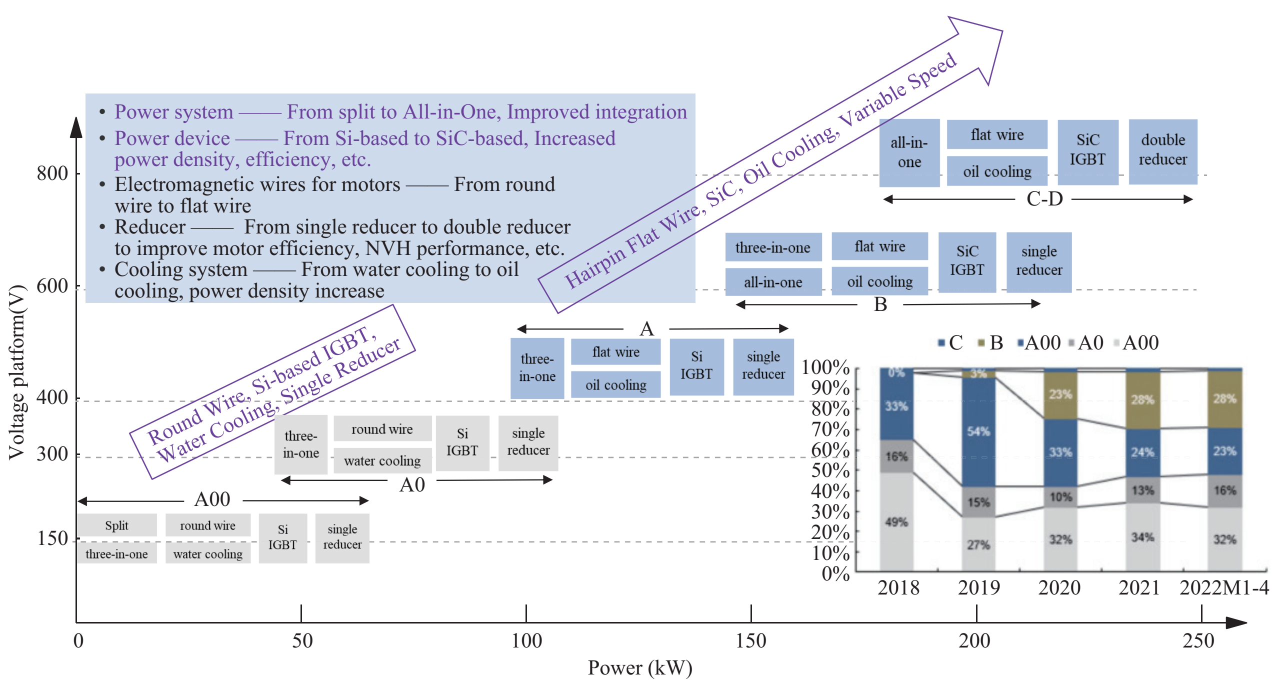

Fig. 3. Technical program of new energy vehicle electric drive system.

proposed by Professor Cai to reduce overall winding losses and ensure a more uniform distribution in all flat wires at different slot locations. Consequently, the future development of flat wire winding technology is expected to move toward variable cross-section windings.

In the realm of power electronic controllers, power devices are evolving toward SiC. Throughout this development, some challenges have to be faced, such as (1) high temperature tolerance and heat dissipation and (2) parasitic inductance, etc., and electromagnetic compatibility. Currently, temperature tolerance of film capacitors is limited to only 105°C, posing a bottleneck in high temperature SiC module application. A novel approach emerging abroad involves transforming the voltage-source inverter into Instead of voltage source inverter (VSI), the current-source inverter is revived by Thomas Jahns at University of Wisconsin at Madison [18], facilitating the substitution of film capacitors with ceramic capacitors for improving system's temperature tolerance, from 105°C to over 150°C. Key technologies crucial for this development include double-sided sintering of wire bonding and enhanced temperature resistance of film capacitors. In order to better utilize the high-temperature resistance of SiC and reduce parasitic parameters, SiC power module sintered packaging is applied to replace bonding wire packaging, and the silver paste is widely used globally in the process [19]. Compared with silver paste, copper paste has advantages of high reliability and low cost. Copper paste and the copper film are developed by HUST's research group [20], and the sintering SiC modules are being tested well.

V. Professor Song: Utilizing V2G to Achieve Carbon Neutrality in Power and Transportation Systems

V2G is a promising solution to help achieve carbon neutrality in power and transportation systems. According to the IEA, the top two carbon-emitting sectors in 2020 are power generation and heating, and transportation [21]. Therefore, carbon reduction in power and transportation systems is crucial for achieving carbon neutrality. Carbon reduction requires innovation in power systems. A new power system, characterized by a significant reliance on renewable energy sources, faces challenges due to the random and intermittent nature of renewable power generation [22]. High penetration of renewable power generation may lead to significant mismatches between power supply and demand in power systems, which might deteriorate power systems' economy and security. As a result, regulating demand on the consumer side to tackle these mismatches is essential. Additionally, the rapidly growing number of EVs coupled with disordered charging patterns poses a significant strain on the power system. Deviation of the electricity demand for EVs from renewable power generation may exacerbate peak-valley grid discrepancies, thereby increasing carbon emissions. Hence, V2G is an inevitable requirement for large-scale integration of EVs into the grid toward low-carbon development.

V2G has been a research hotspot in both academia and industry in the last decade. Many V2G pilot projects have already been successfully demonstrated worldwide. V2G technology connects the energy storage capacity of EVs with the power grid to achieve bidirectional energy flow. It helps realize mutual profits between the EV industry and power system, improves power grid stability and reliability, promotes EV popularization and development, and provides new business opportunities and profit models. The UK Power Grid Corporation has counted 50 V2G projects around the world, which involve price arbitrage, backup services, frequency response, distribution network services, load shifting, and other service types [23]. In addition, many pilot projects are also successfully conducted in China, involving orderly charging, virtual power plants, retired battery utilization, and other services. These projects prove the feasibility of the V2G technology. However, the V2G bidirectional charger has high cost, significant energy loss, and an immature business model, which need further innovations.

Two optimization questions are essential for V2G applications. How to properly plan charging infrastructure to satisfy large-scale spatiotemporal uncertain EV charging demands and how to optimize EVs' charging and discharging processes to reduce system carbon emissions and promote social welfare. To solve these problems, charging load prediction, infrastructure planning, and charging & discharging dispatching are the areas of focus. In terms of flexibility assessment and regulation of charging load, based on the charging load characteristics of EVs, a storage-like aggregate model for large-scale heterogeneous EVs is established, and a hierarchical regulation framework is further proposed to realize dynamic aggregated regulation of large-scale EVs [24], [25]. In terms of charging infrastructure planning, multi-chargers, multi-interface charging systems at charging stations, and an optimized configuration method are developed. Furthermore, a charging & discharging network planning method, taking into account the comprehensive considerations of power-and traffic-coupled network constraints, offers novel solutions to enhance the investment efficiency of charging facilities and to address the challenges in modeling and solving complex charging infrastructure planning problems. In addition, an algorithm and model of charging pricing and vehicle scheduling, power, and transportation coordination were introduced to promote benign interactions between smart grids and intelligent transportation. Fig. 4 shows an optimal traffic flow guidance strategy for social benefits. Based on a novel intercity highway network expansion model considering vehicle path selection, traffic flow optimization aims to minimize overall social costs, including user time and power supply costs for the grid. [26]

Finally, peak load shaving, frequency regulation, and reserve capacity provision through V2G may be replaced by a fixed energy storage system; therefore, only economic advantages can scale V2G development.

VI. Professor C.C. Chan: Grasp Engineering Philosophy and Cultivate Scientific Spirit—Re-examining the Profound Development of EVs

Two ongoing revolutions are as follows: First, the energy revolution, pivoting toward carbon peaking and carbon neu-

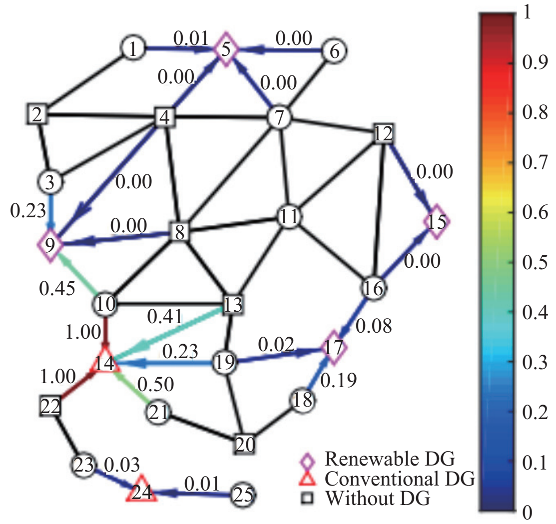

Fig. 4. Traffic flow optimization results. © [2020] IEEE. Reprinted, with permission, from [26].

trality goals, finds its core solutions in low-carbon, intelligence technology, electrification, and hydrogen energy. This revolution champions development of new power systems characterized by safety, efficiency, cleanliness, and low-carbon emissions. These systems emphasize multisource complementarity, orchestrating cohesive coordination between the power supply, power grid, demand load, and energy storage, thereby fostering a flexible and intelligent infrastructure capable of balancing random fluctuations in supply and demand. Second, the automotive revolution aims to achieve smart transportation and smart cities, focusing on sustainable development and continuous explosive growth of new energy vehicles [27]. Here, the shift toward pure EVs emerges as a dominant force, constituting nearly 80% of the total new energy vehicle landscape, albeit facing the challenges of limited energy density and short driving ranges at lower costs.

To address these challenges, digital solutions for EV charging and swapping were proposed (see Fig. 5). These solutions require leveraging EVs as mobile energy storage and emergency power supplies and involve interconnected charging

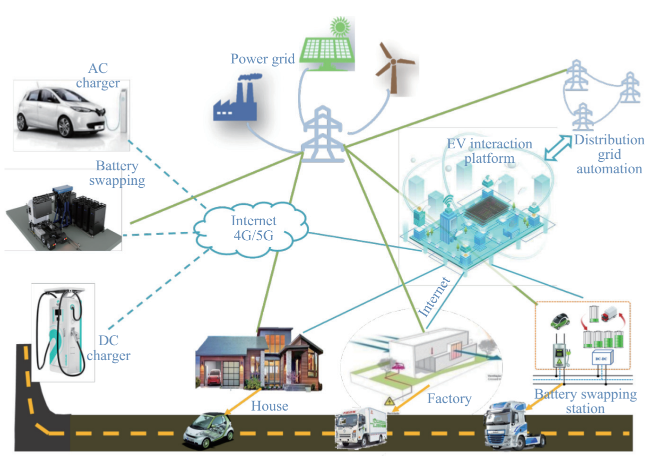

Fig. 5. Digital solutions for EV charging and swapping.

equipment, user-friendly charging operations, and tapping into the intermittent complementarity between new energy sources and EVs [28].

The concept of "Integration of Four Networks & Four Flows" was introduced [29]. Focusing on energy networks, transportation networks, information networks, cultural networks, and energy flows, information flow, material flow, value flow, interconnection, interaction, and integration across these multiple sectors are essential. This concept aims to resolve sustainability challenges posed by the Industrial Revolution and promote development of smart energy ecosystems, fostering carbon balance and sustainable growth. Ultimately, this interplay builds a low-carbon, safe, efficient, and comfortable transportation system through intelligent systems. Seamless synergy between vehicles, roads, and cities creates a carbon-neutral smart energy ecosystem, heralding a new era of urban development and sustainability.

VII. Conclusion

This study presented opinions on key technologies and prospects for new energy vehicles in new power systems. Specifically, Professor Ouyang emphasized the supportive role of energy storage using EVs in new power systems and its technical framework. Professor Sun proposed that ASSBs using halide electrolytes have significant potential but faces several challenges in material synthesis and manufacturing. Professor Cai introduced product innovation and technological frontiers of the industry chain in electric motor systems and highlighted the future directions of electric drive systems. Professor Song discussed the progress of global vehicle–grid integration demonstration projects, emphasizing the significance of optimizing vehicle spatiotemporal uncertainties and charging/discharging processes. Professor Chan re-examined the profound development of EVs and addressed the importance of 4 networks and 4 flow integration. The major viewpoints of the experts are summarized below.

1) Energy storage capacity of power batteries in new energy vehicles exhibits substantial potential in both the power and energy domains. When aggregated, it is poised to emerge as the most extensive, cost-effective, and universally applicable energy storage unit. Given pronounced technological convergence between new energy power systems and new energy electric power systems, realizing an efficient V2G requires establishing high-, medium-, and low-frequency technical frameworks for grid operations, power generation and transmission, power distribution and microgrid, aggregator, and charging infrastructure.

2) Halide solid-state electrolytes are a crucial material for next-generation all-solid-state batteries. Ongoing efforts focus on improving their properties through innovative structural design and synthesis approaches. Advanced characterization techniques and theoretical simulations have been instrumental in elucidating the ion transport mechanisms of halide electrolytes and driving their development. Scaling up production remains a hurdle, with an emphasis on large-scale production and adoption of dry electrode technology to reduce costs.

Overcoming these challenges is crucial for practical application of halide SSEs in ASSBs, which offers promising solutions for future energy storage.

3) High-power-density, high-performance motor drive technology represents a critical direction for future EV development. Currently, a gap exists between domestic and international advancements in this field. This technological domain requires advancing techniques such as high-speed motors with surface-mounted permanent magnet technology, variable cross-sectional winding technology, high-switching-frequency and high-temperature-resistant semiconductors, and capacitor technology. Simultaneously, technologies such as self-adhesive silicon steel sheets, low rare-earth content, and non-rare-earth material permanent magnets require increased attention.

4) V2G technology holds promise for emerging power systems, and demonstrative projects are rapidly proliferating. Achieving this integration necessitates addressing the spatiotemporal uncertainties associated with EV charging demands and managing energy scheduling during C&D processes. Charging load prediction, infrastructure planning, and charging/discharging scheduling technologies are necessary to resolve the aforementioned challenges.

5) The digital evolution of EV charging and swapping is actively facilitating integration of EVs as intelligent storage and power supply units into the grid. Throughout the energy revolution, interconnectedness, interaction, and integration across multiple sectors—energy, transportation, information, and economic networks and flows—are crucial.

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