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

P Phani
Assistant Professor
Department of Electrical
And Electronics Engineering,
Ramachandra College of
Engineering, India

Ch Sabitha
Assistant Professor
Department of Electrical
And Electronics Engineering,
Ramachandra College of
Engineering, India

B Pathrisamma
Assistant Professor
Department of Electrical
And Electronics Engineering,
Ramachandra College of
Engineering, India

Narendra Bavisetti
Assistant Professor
Department of Electrical
And Electronics Engineering,
Ramachandra College of
Engineering,India

Abstract : Coordination in energy supply, storage, consumption, and institutional structures is necessary for the energy revolution. The cost of producing renewable energy is already completely prepared for widespread marketing, as are the technology associated with it. Though electric cars often play the function of energy consumption in power systems, energy storage remains a bottleneck, necessitating solutions. The CSEE JPES forum brought together prominent experts and scholars in pertinent fields to conduct keynote speeches and panel discussions on a range of topics, including vehicle–grid integration technology ,advanced solid-state battery technology, high-performance electric motor technology, and institutional innovation in the industry chain. The aim of the forum was to elucidate the critical technologies and institutions that facilitate EVs as terminals for energy use, storage, and feedback. Experts discussed energy storage and usage methods that can reduce carbon emissions in modern power systems.

Keywords- Electric vehicles, engineering philosophy, high- power density motor, new power system, solid state batteries, vehicle grid integration.

I. INTRODUCTION

To completely elucidate the state of technology and development trends surrounding the use of electric vehicles (EVs) as energy storage Received on January 10, 2024; updated on January 25, 2024; approved on February 5, 2024. Date of current version: March 1, 2024; date of online publication: February 14, 2024. The National Key Research and Development Project of the Ministry of Science and Technology of China, under Grant 2022YFE0103000, and the Tsinghua-Toyota Joint Research and China National Postdoctoral Program for Innovative Talents, under Grant BX20220171, provided additional funding for this study. Y. L. Li works at Tsinghua University's School of Vehicle and Mobility and Department of Electrical Engineering, Beijing 100084, China. She helped to finalize the paper based on feedback from forums. Y. L. Xie, Y. Q. Mao, and M. G. Ouyang (corresponding author who helped with forum organization; email:ouymg@tsinghua.edu.cn, liyalun@tsinghua.edu.cn) are affiliated with Tsinghua University's School of Vehicle and Mobility, Beijing 100084, China. C. C. Chan works at The University of Hong Kong, 999077, China, in the Department of Electrical and Electronic Engineering. X. L. Sun works at the University of Western Ontario's Department of Mechanical and Materials Engineering, located in London, ON N6A 3K7, Canada. Y. H. Song is affiliated with the Department of Electrical Engineering, Tsinghua University, Beijing 100084, China, as well as the State Key Laboratory of Internet of Things for Smart City, University of Macau, Taipa, Macau 999078, China. W. Cai works at the Harbin University of Science and Technology's School of Electrical and Electronic Engineering, located in Harbin, 150080, China. CSEEJPES.2024.00190 DOI: 10.17775 a thorough analysis and discussion of the energy and power system technology of EVs is crucial for units in developing power systems.

In order to gather expert and scholarly opinions on the latest developments in distributed energy storage devices, next-generation battery technology, advanced motor technology, vehicle to grid technology, and EV engineering philosophy, CSEE JPES organized a forum on the key technologies and prospects for EVs within emerging power systems. This text presents the main scholarly opinions in the field. Professor Ouyang examines the need, viability, and technological framework of EVs as dispersed energy storage units in a power system in Section II. Professor Sun outlines the technological paths to implement solid-state batteries using halide electrolytes in Section III. Professor Cai outlines the difficulties and technological limits of an improved motor and propulsion system in Section IV. Professor Song outlines the essential technologies to address the vehicle-to-grid uncertainty in Section V. Professor Chan addresses engineering philosophy and cultivating a scientific mindset in the creation of electric vehicles in Section VI. Section VII, the paper's conclusion, provides an overview of the experts' principal points of view.

II. PROFESSOR OUYANG: EVS AND NEW POWER SYSTEMS—PROSPECTS OF VEHICLE–GRID INTEGRATION TECHNOLOGY

Although China has the highest installed capacity for producing new energy power worldwide, there are still concerns about this energy source's unpredictability. Grid stability is also threatened by the rapidly expanding number of new energy vehicles, especially when it comes to supercharging. The pressing requirement for a novel energy-storage-based power system becomes apparent, underscoring the increasing focus on batteries. In light of this, using vehicle-to-grid (V2G) technology to solve issues with grid stability and charging capacity is the key to finding a solution. Peak shaving is made possible by EVs when they are parked and linked to the grid via bidirectional charging stations. The combination of user, corporate, and governmental participation creates a synergy that presents EVs as energy trading catalysts, offering significant financial gains to all parties involved. Additionally, V2G storage—a low-cost, secure type of distributed energy storage—has revolutionized the energy storage industry. By 2040, predictions indicate extraordinary potential—300 million electric vehicles are expected to have a combined capacity of over 20 billion kWh, or more than China's daily power usage [1]. An extensive examination of V2G apps and technical frameworks was revealed in this area. Electric vehicles (EVs) may be carefully matched with medium-voltage distribution networks, such metropolitan highway charging stations, and low-voltage distribution networks, like residential zones.
Power equipment (such photovoltaics and wind turbines), communication infrastructure, and gateway systems are all integrated into a technological platform. Many functions like energy management, load aggregation, energy trading, market services, and load and travel forecasts specific to electric vehicles are supported by this integration. To elaborate on this story, the V2G system requires study on optimal management for full-band frequency (see Fig. 1). Virtual synchronous machines, droop-based inertia control techniques, and active and reactive power decoupling control techniques were introduced with regard to high-frequency power grid stability management [2]. A method employing voltage signals to represent internal energy balance while reducing control and communication complexity, and therefore enabling synchronized operation between energy sources and loads, was developed for high to mid-frequency microgrid power distribution and energy management. Additionally, an interactive control approach based on thermoelectric coupling models and power market mechanisms was introduced to optimize the management of mid-frequency power batteries in an effort to maximize economic benefits [3]

III. PROFESSOR SUN: ADVANCEMENTS AND CHALLENGES IN NOVEL HALIDE SOLID-STATE BATTERIES

The portable electronics sector has seen a significant transformation because to the widespread use of conventional lithium-ion batteries (LIBs). The physicochemical energy density limit of LIBs and possible safety issues related to flammable organic liquid electrolytes have, however, drawn criticism as their use has grown. In addition to offering increased safety, all-solid-state lithium batteries (ASSLBs) have the potential to achieve great energy density since they use solid-state electrolytes (SSEs) rather than flammable liquid electrolytes. These batteries have garnered a great deal of attention and are acknowledged as the most promising next-generation energy storage technology due to their ability to operate over a wide temperature range. Significant progress in halide solid-state electrolytes has been achieved, garnering significant interest for their potential use in ASSLBs. At ambient temperature, these electrolytes show extensive electrochemical win- dows,

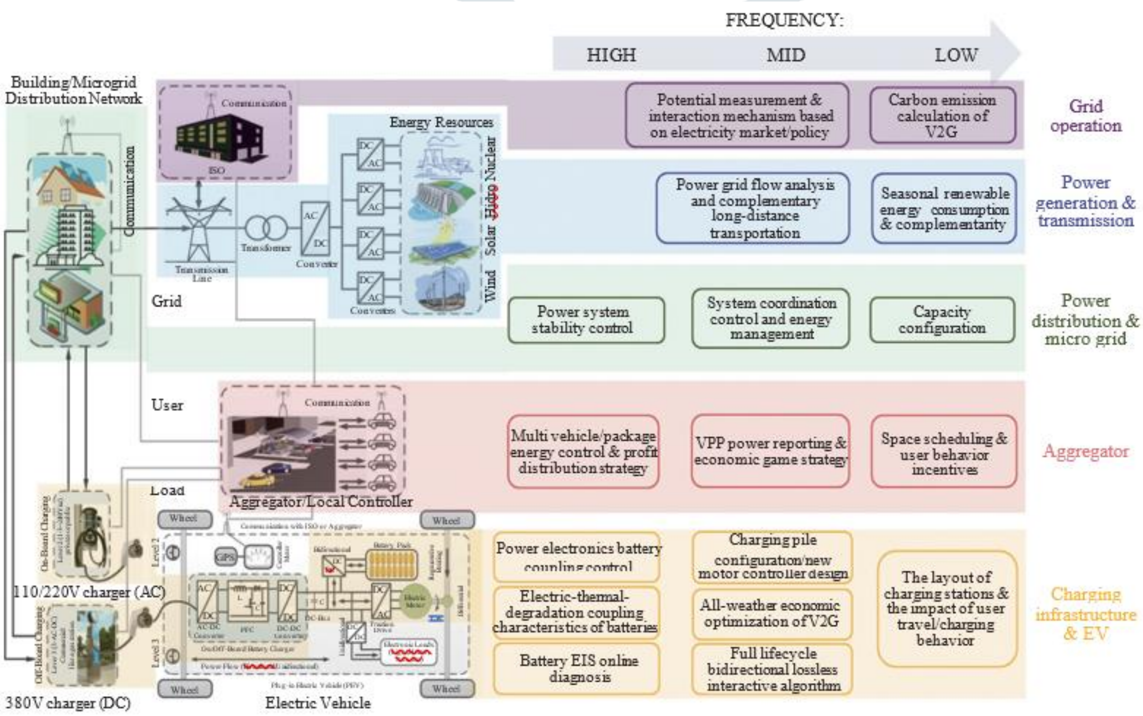

Fig. 1. Research on optimized control for the full-band frequency of the V2G system.

Many approaches have been investigated for halide solid-state electrolyte production, with liquid-phase synthesis showing particular promise [10]. Due to its special qualities and affordability, this approach has great promise for improving halide SSEs. Furthermore, methodologies including structural design, creative synthesis, and simulation calculations are employed to improve the physical and chemical characteristics of halide SSEs [11], [12]. These efforts are intended to assure chemical and electrochemical stability in critical areas such as thermal stability, resistance to air and humidity, compatibility with cathodes and anodes, and inherent electrochemical stability windows, in addition to ensuring compatibility with high voltages. Researchers have examined interface processes including ion and electron transport between halide SSEs and cathode/anode using thin film methods such as ALD/MLD interfacial coating design and in-situ characterization (e.g., in-situ XAS, Raman, XRD) [13]. They discovered that halide solid-state electrolytes outperform their sulfide counterparts in terms of cathode compatibility, oxidation limit, and moisture stability. There are many obstacles in the way of using halide solid-state electrolytes in energy storage for practical use. Resolving the large-scale manufacture of solid electrolyte materials is the main issue in increasing the production of solid-state batteries. Applying dry electrode methods and utilizing the extremely promising dry method manufacturing technology are also essential for creating ultra-thin inorganic solid electrolyte sheets. It is anticipated that the use of dry electrode technology would greatly lower the total production costs of all-solid-state batteries in addition to being beneficial for the preparation of solid-state batteries [14]. Getting beyond these obstacles will lay the groundwork for the use of halide solid-state electrolytes in ASSLBs, which provide more viable options for energy storage in the future (see Fig. 2).

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

Propulsion motors, power electronic controllers, reduction/transmission gearboxes, and other essential parts, electronics, and materials make up the industrial chain for electric drive systems. China has achieved notable advancements and enhanced its capacity for self-sufficiency in electric drive systems, assemblies, power modules, and materials in the past few years. At present, domestic electric drive assemblies are widely used, with a market share of more than 50% for domestic insulate-gate bipolar transistor (IGBT) chips and power modules. Nonetheless, fewer than 8% of microcontroller units and silicon carbide (SiC) are still produced domestically. China continues to lag behind other sophisticated motor technology nations in terms of both leading motor research and high-end motor technology manufacturer. NC State University has reached the U.S. Department of Energy's objective of a motor power density of 50 kW/L. The system consists of a surface-mounted permanent magnet rotor and centralized stator windings using carbon nanotube superconducting copper. Prototype motors have been constructed and evaluated. Presenting the electric powertrain product at Lucid Air Motors, Peter Rowlinson boasts a 500 kW power output and a mere 74 kg mass [15]. A variety of novel topologies and design advancements were introduced, including planetary gears, flat wire wave-windings, oil cooling with cooling channels positioned at the roots of the winding iron core, and sintered and bonded permanent magnets with a dual V configuration. It has proven possible to reach the effective power density of 15.65 kW/kg for the motors [16] and 6.76 kW/kg for the total electric powertrain, which includes the motor, controller, and reducer. By contrast, domestic Performance and motor technology are still far behind. Chinese OEM Aion of Guangzhou Automobile Group Co. Ltd. achieves an effective power density of 12 kW/kg at 15 seconds, whereas Chinese OEMs and suppliers achieve effective material power densities of 4.5 to 7 kW/kg for mass-produced motors.

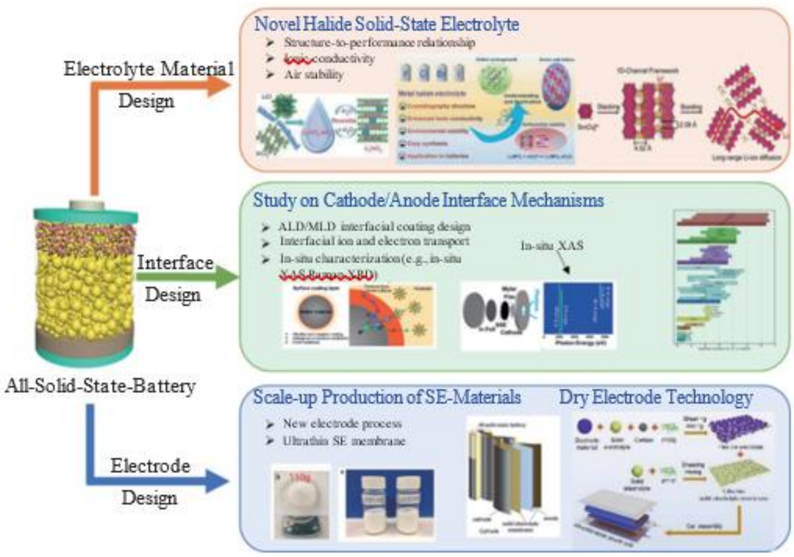

Fig. 2. Summary and outlook on key materials and battery technology for all-solid-state batteries.

Fig. 3 presents the technology routes and development patterns in the electric drive sector. Single-stage reduction gear technologies, silicon-based semiconductors, strand round wire dispersed windings, water indirect cooling for heat dissipation, and heat-dissipating water cooling may all be used to power new energy vehicles below Class A that have low power and low voltage. The technologies will be gradually moved to the use of flat wire motors, SiC semiconductor modules, oil direct cooling or oil direct combined with indirect-water cooling for heat dissipation, multi-stage gear reducers, or multi-speed transmissions as voltage and power increase and vehicles electric powertrains for above Class B. Power density and efficiency growth, which strive to lower the size of high efficiency motors, are the primary trends in the development of electric motors. To do this, torque decrease and speed elevation are required. Power devices with low switching frequencies may cause problems including non-sinusoidal currents and noise in the air. Consequently, raising the motor controller's switching frequency is necessary to increase motor speed. Third-generation wide-bandgap semiconductors are an essential step because they offer improved temperature resistance and efficiency. It's also crucial to match the gear reducer to the wheel speed. In order to achieve high-power-density motors, it is imperative to remove the heat dissipation bottleneck, which entails maximizing heat dissipation efficiency, reducing pump power consumption, and guaranteeing system strength. Lastly, consideration of insulation concerns is also necessary when raising the controller's switching frequency.

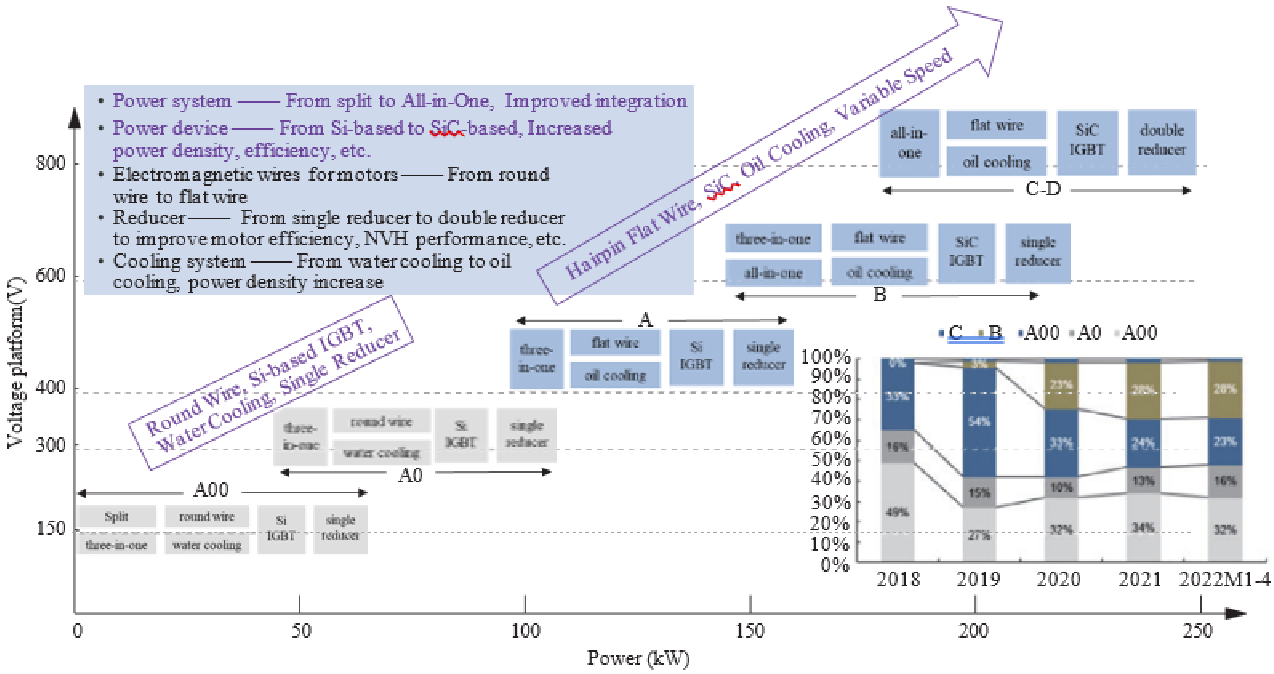

Fig. 3. Technical program of new energy vehicle electric drive system.

Since motor torque can be increased from resistance torque through inductance difference between Q-axis and D-axis, interior permanent magnets (IPM) arranged in configurations, such as double-V and triangular arrangements, are primarily incorporated in the rotor of permanent magnet motors as they currently exist. However, surface-mounted permanent magnet (SPM) motors start to show benefits once rotational speeds reach above 20,000 rpm. This is because high speed IPM motors will have considerable rotor flux leakage due to the need for stronger magnetic bridges to fulfill structural strength requirements. All American Department of Energy project developers have recently started using the SPM topology. These permanent magnets are arranged in a Halbach array, which helps to produce an airgap magnetic field with minimal harmonic distortion and noise that is more sinusoidally distributed. Specifically, focused windings and SPM implementation should work together. Professor Cai made a proposal for high voltage "hairpin" flat wire winding technology in the field of winding innovation [17]. This technology is now widely used for high efficiency propulsion motors. His developed flat wire wrapping technology yields high slot-filled factor, high efficiency, high power density, low bulk, etc. However, if the thickness of the flat wires in slots grows, eddy current losses will increase with frequency or speed and lead to relatively large total AC resistance losses. The loss in each flat wire varies with its position in a slot, even if the number of layers of flat wires in the slot might be increased to minimize AC resistance losses. For example, the flat wire at the slot entrance has more AC resistance and more thermal difficulties; the flat wire at the bottom of the slot has much better conditions, but it is specifically mismatched with the cooling channel construction for the water cooling system. Stepped slot width is coupled with end-turn transitioning multi-strand flat wire and variable thickness flat wires, which are suggested by Professor Cai in order to guarantee a more uniform distribution in all flat wires at various slot positions and lower total winding losses. Consequently, variable cross-section windings are anticipated to be the direction of future advancements in flat wire winding technology. Power devices in the field of power electronic controllers are moving in the direction of SiC. Several obstacles must be overcome throughout its development, including (1) high heat dissipation and temperature tolerance and (2) parasitic inductance, etc., and electromagnetic compatibility. Film capacitors' current 105°C temperature tolerance places a restriction on their use in high-temperature SiC modules. One innovative method that is making its way overseas is converting the voltage-source inverter into Thomas Jahns at the University of Wisconsin at Madison revives the current-source inverter [18] in place of the voltage source inverter (VSI), allowing ceramic capacitors to be used in place of film capacitors to improve the system's temperature tolerance from 105°C to over 150°C. The development of double-sided wire bonding sintering and improved temperature resistance in film capacitors are critical technologies. SiC power module sintered packaging is employed to replace bonded wire packaging in order to better exploit the high-temperature resistance of SiC and lower parasitic characteristics; silver paste is extensively used internationally in this procedure [19]. The benefits of copper paste over silver paste include its low cost and great dependability. The research team at HUST produced the copper paste and copper film [20], and the SiC sintering modules are being thoroughly tested.

V. PROFESSOR SONG: UTILIZING V2G TO ACHIEVE CARBON NEUTRALITY IN POWER AND TRANSPORTATION SYSTEMS

In order to assist in achieving carbon neutrality in the transportation and electricity networks, V2G is a possible approach. The two industries that will emit the most carbon in 2020, according to the IEA, are transportation and electricity generation and heating [21]. Therefore, attaining carbon neutrality requires reducing carbon in the electricity and transportation networks. Power system innovation is necessary for reducing carbon emissions. The unpredictable and sporadic nature of renewable power generation presents difficulties for a new power system that heavily depends on these sources of energy [22]. High penetration of renewable power generation might result in major imbalances between supply and demand for electricity in power systems, which could impair the security and economy of those systems. Therefore, controlling consumer demand is crucial to addressing these mismatches. In addition, the power grid is severely strained by the steadily increasing number of EVs combined with irregular charging schedules. When EV electricity consumption deviates from renewable power output, peak-valley grid disparities may be aggravated, leading to a rise in carbon emissions. In order to integrate EVs into the grid on a significant scale and move toward low-carbon development, V2G is therefore a necessary prerequisite. Over the past ten years, V2G has been a popular topic for research in both academia and business. Numerous V2G test initiatives have been effectively shown all around the world already. In order to accomplish bidirectional energy flow, V2G technology integrates the energy storage capacity of EVs with the power grid. It enables the EV industry and the power system reach mutually beneficial outcomes, enhances the stability and dependability of the power grid, encourages the growth and popularization of EVs, and offers new business prospects and profit models. Fifty V2G initiatives involving price arbitrage, backup services, frequency response, distribution network services, load shifting, and other service kinds have been tallied by the UK Power Grid Corporation globally [23]. Furthermore, China has successfully carried out a number of pilot projects pertaining to orderly charging, virtual power plants, retired battery usage, and other services. These initiatives demonstrate that V2G technology is feasible. Nevertheless, the V2G bidirectional charger need further innovation due to its high cost, large energy loss, and immature business strategy. For V2G applications, there are two key optimization problems. How to optimally design the infrastructure for EV charging in order to meet the expectations of EV users for large-scale, spatiotemporal uncertainty in charging, as well as how to minimize carbon emissions from the system and advance societal welfare. The areas of attention for solving these issues include charging load prediction, infrastructure design, and charging and discharging dispatching. Regarding charging load regulation and flexibility assessment, a storage-like aggregate model for large-scale heterogeneous EVs is established based on EV charging load characteristics. A hierarchical regulation framework is further proposed to realize dynamic aggregated regulation of large-scale EVs [24], [25]. Multi-chargers, multi-interface charging systems at charging stations, and an optimum setup technique are created in terms of charging infrastructure design. Moreover, a method for planning charging and discharging networks that takes into account the full range of power-and traffic-coupled network constraints presents innovative ways to improve the return on investment of charging stations and overcome the difficulties associated with modeling and resolving intricate charging infrastructure planning issues. To encourage positive interactions between smart grids and intelligent transportation, an algorithm and model of charging price, vehicle scheduling, power, and coordination

VI. PROFESSOR C.C. CHAN: GRASP ENGINEERING PHILOSOPHY AND CULTIVATE SCIENTIFIC SPIRIT—RE-EXAMINING THE PROFOUND DEVELOPMENT OF EVs

There are currently two revolutions in progress: Initially, the energy revolution finds its fundamental answers in low-carbon, intelligent technologies, electrification, and hydrogen energy as it turns toward carbon peaking and carbon neutrality goals.

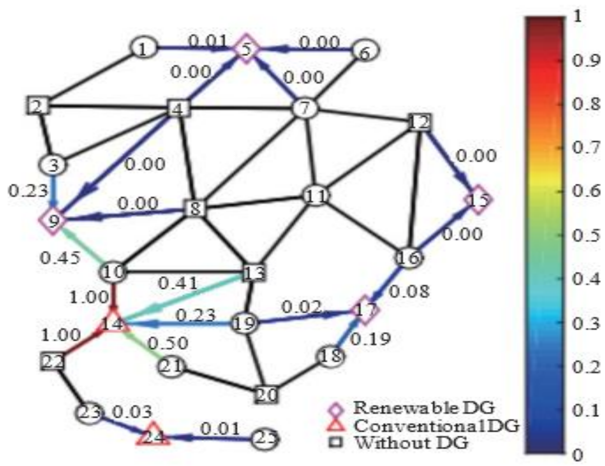

Fig. 4. Traffic flow optimization results. © [2020] IEEE. Reprinted, with permission, from [26].

The development of new power systems with minimal carbon emissions, safety, efficiency, and cleanliness is encouraged by this revolution. These systems place a strong emphasis on multisource compatibility, coordinating the power supply, power grid, demand load, and energy storage in a coherent manner. This promotes an adaptable and intelligent infrastructure that can balance erratic variations in supply and demand. Second, the automotive revolution is focused on sustainable development and the ongoing, exponential expansion of new energy vehicles with the goal of achieving smart cities and smart transportation [27]. Here, the trend toward all-electric vehicles (EVs) takes center stage, accounting for about 80% of the new energy vehicle market, despite the obstacles of low energy density and short driving ranges at reduced prices. Digital EV charging and switching methods were suggested as a solution to these issues (see Fig. 5). These solutions entail connecting charging infrastructure, making charging simple for users, and using the intermittent complementarity between EVs and new energy sources. They also need using EVs as mobile energy storage and emergency power supplies [28].

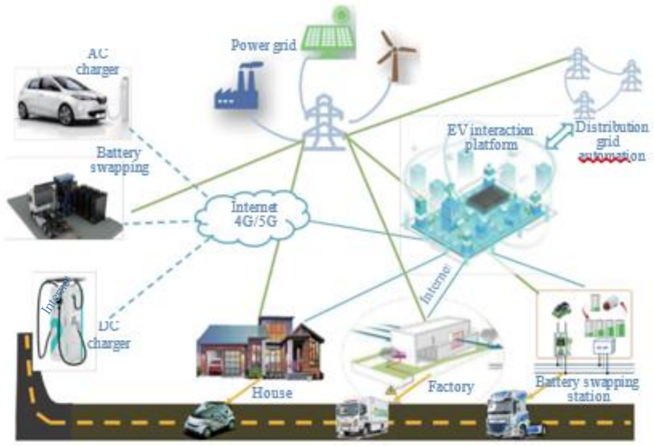

Fig. 5. Digital solutions for EV charging and swapping.

[29] proposed the idea of "Integration of Four Networks & Four Flows." It is imperative to concentrate on the energy, transportation, information, and cultural networks as well as the energy, information, material, and value flows, as well as the connectivity, interaction, and integration among these many sectors. This idea seeks to address the problems with sustainability brought about by the Industrial Revolution and encourage the establishment of intelligent energy ecosystems, therefore preserving carbon balance and fostering sustainable development. In the end, this interaction creates intelligent systems that enable a low-carbon, secure, effective, and comfortable transportation system. A new age of urban growth and sustainability is ushered in by the seamless interaction of cars, highways, and cities to create a carbon-neutral smart energy environment.

VII. CONCLUSION

Opinions on important technologies and future possibilities for new energy vehicles in new power systems were offered in this study. Professor Ouyang focused on the technological framework and assisting function of energy storage with EVs in modern power systems. ASSBs employing halide electrolytes, according to Professor Sun, offer a lot of promise but confront a number of difficulties in the synthesis and production of the materials. Professor Cai outlined the future directions of electric drive systems and provided an introduction to technological boundaries in the industry chain for electric motor systems as well as product innovation. Professor Song talked about the development of worldwide demonstration projects for vehicle-grid integration while highlighting the need of improving vehicle spatiotemporal uncertainty and charging/discharging procedures. Professor Chan revisited the significant evolution of electric vehicles and talked about the significance of four networks and four flow integration. Below is a summary of the experts' main points of view.

1) The power and energy sectors show significant promise for the energy storage capacity of power batteries in future energy vehicles. When combined, it will be the largest, most affordable, and most widely used energy storage device available. In order to realize an efficient V2G, high-, medium-, and low-frequency technical frameworks for grid operations, power generation and transmission, power distribution and microgrid, aggregator, and charging infrastructure must be established. This is because new energy power systems and new energy electric power systems have clearly converged technologically.

2) A key component of next-generation all-solid-state batteries are halid solid-state electrolytes. Continuous endeavors center on enhancing their characteristics by means of inventive structure design and synthesis methodologies. The development of halide electrolytes and the clarification of their ion transport processes have been facilitated by sophisticated characterisation methods and theoretical simulations. With a focus on large-scale production and the use of dry electrode technology to cut costs, scaling up production is still a challenge. The practical application of halide SSEs in ASSBs, which presents encouraging options for future energy storage, depends on overcoming these obstacles.

3. A crucial path for EV development in the future is high-power-density, high-performance motor drive technology. There is now a divide in this sector between developments made domestically and internationally. This field of technology demands advancements in areas like capacitor technology, variable cross-sectional winding, high-switching-frequency and high-temperature-resistant semiconductors, and high-speed motors with surface-mounted permanent magnet technology. At the same time, more focus is needed on technologies such permanent magnets made of non-rareearth materials, low rare-earth content, and self-adhesive silicon steel sheets.

4) V2G technology is promising for developing power systems, and there are a growing number of demonstration projects. Resolving the spatiotemporal uncertainty related to EV charging demands and controlling energy scheduling throughout C&D

processes are necessary to achieve this integration. To address the aforementioned issues, methods for charging load prediction, infrastructure design, and charging/discharging scheduling are required.

5) The digital transformation of EV charging and swapping is aggressively promoting EV integration into the grid as intelligent power supply and storage devices. Interconnectedness, interaction, and integration of many sectors—energy, transportation, information, and economic networks and flows—are essential throughout the energy revolution.

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