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Overview of Superconductors and Their Diversified Applications

Rui LYU*,, Calvin C. T. CHOW*, Wei LIU*, Yunhe HOU**, C. C. CHAN*, and K. T. CHAU*†**

Abstract – Superconductors were discovered more than a century ago, and they have transformative applications due to their unusual properties of zero DC resistance, high current-carrying capacity, Meissner effect and Josephson effect. Key domains of superconductor applications include power transmission cables, high power density electric machines, wireless power transfer, magnetic gears, magnetic energy storage, fusion reactors, magnetic resonance imaging, and some advanced systems. Challenges such as material fragility, AC losses, and cryogenic requirements necessitate sophisticated modeling and material advances. Overcoming these hurdles will unlock HTS potential for next-generation electrical efficiency and capability.

Keywords: High-temperature superconductors (HTS), HTS materials, electromagnetic modeling, HTS applications

1. Introduction

The discovery of high-temperature superconductors (HTSs) over four decades ago marked a paradigm shift in material science and electrical engineering. Unlike conventional low-temperature superconductors (LTSs) that require costly and complex liquid helium cooling, HTS materials exhibit critical temperatures above 30 K, and some can be cooled with relatively inexpensive liquid nitrogen [1]. This fundamental advantage, coupled with their exceptional current-carrying capacity and ability to withstand high magnetic fields, has propelled HTSs from a laboratory curiosity to a useful technology for next-generation electrical systems.

The transformative potential of HTSs is rooted in their defining properties: zero electrical resistance and the Meissner effect (perfect diamagnetism) [2]. However, harnessing these properties for practical applications presents significant challenges, including the brittle nature [3] of many HTS materials and AC loss, which are energy losses under time-varying magnetic field or when the superconductors carry AC [4]. Consequently, sophisticated electromagnetic modeling to predict AC loss has become indispensable. Numerical simulation techniques, particularly the finite element method (FEM) are crucial for analyzing nonlinear electromagnetic behavior, optimizing device performance, and guiding engineering design [5].

This paper provides a comprehensive review of superconductor technologies and their diverse applications, which are progressing along varying technology-readiness timelines. Mature superconductor technology currently in use includes magnetic resonance imaging (MRI) scanners, particle accelerator magnets and superconducting quantum interference device (SQUID) sensors. Prominent short to medium-term applications include high power density electric machines for aviation and renewable energy, highly efficient power transmission cables for urban grids, and advanced wireless power transfer (WPT) systems [6]. Furthermore, HTSs are enabling revolutionary long-term advancements in areas such as compact fusion reactors through high-field magnets, scalable quantum computing, and future ultra-precision measurement instruments. This review explores these domains, highlighting how HTS technologies are poised to deliver transformative impact across the electrical and electronic engineering landscape, from giant power systems to tiny quantum devices.

2. HTS Materials

HTSs are a transformative class of materials that maintain superconductivity at significantly elevated temperatures, making cooling systems simpler and more economical [7]. This stands in stark contrast to conventional superconductors, which require costly and complex liquid helium systems. The shift to nitrogen-based cooling fundamentally improves the economic feasibility of large-

† Corresponding Author : Dept. of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, China (k.t.chau@polyu.edu.hk)

* Dept. of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, China (Calvin-c-t.chow @polyu.edu.hk, wei.liu@polyu.edu.hk, c.c.chan@polyu.edu.hk,)

** Dept. of Electrical and Electronic Engineering, The University of Hong Kong, China (lyurui@connect.hku.hk, yhhou@eee.hku.hk)

scale superconducting applications. The superconducting state itself is defined by three interdependent critical parameters: the transition temperature (T_c), the critical magnetic field (H_c), and the critical current density (J_c) [8].

T_c is the temperature below which superconductivity occurs; HTS materials typically exhibit T_c values above 30 K, with copper-oxide compounds like YBCO and BSCCO approaching 100 K [9]. This high T_c is the key enabler for using simple liquid nitrogen cooling at 77 K. H_c represents the maximum external magnetic field a superconductor can withstand without losing its zero-resistance state. The enhanced H_c of HTS materials allows for stable operation in the strong magnetic fields required for high-field magnets [10] and fusion reactors [11]. J_c is the maximum electrical current density the material can carry without energy loss. A high J_c is essential for applications, as it enables efficient, high capacity power transmission, high power density motors and generators [12], and HTS fusion reactors [13].

Despite the potential, challenges remain for widespread adoption. The brittle nature of many HTS materials complicates the manufacturing of long, flexible wires [14]. Energy losses under AC and the need for reliable cryogenic systems present further engineering hurdles [15]. Ongoing research focuses on developing more ductile composite wires, improving fabrication techniques, and optimizing cryogenics [16]. In summary, with their high critical parameters and cost-effective cooling, HTS materials represent a pivotal technology. Fig. 1 also summarizes the historical development of key HTS materials.

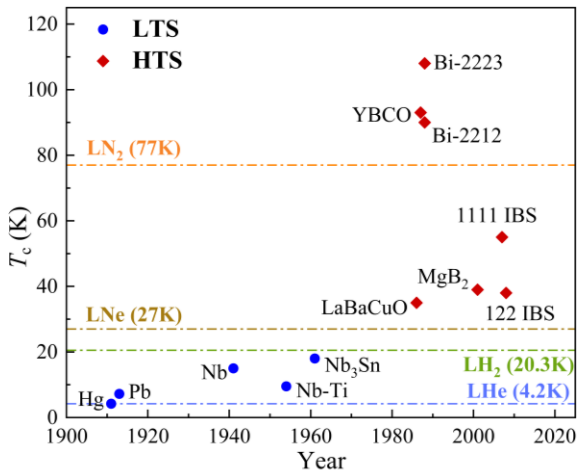


Fig. 1. Development of HTS materials.

3. HTS Modelling

The electromagnetic modeling of HTSs faces unique challenges due to their nonlinear electromagnetic properties, anisotropy, and multiphysics coupling. As HTS modeling evolves from simple superconducting materials to complex devices and large-scale systems, analytical solutions [17] have accuracy limitations, while experimental investigations [18] are time-consuming, challenging, and expensive. Consequently, numerical simulation has become an indispensable tool for optimizing performance, predicting behavior, and guiding engineering design.

Based on [19] and [20], the numerical methods for electromagnetics can be classified according to Fig. 2. The governing equations (derived from Maxwell's equations) can be written in differential or integral forms, e.g., integral forms involving Green functions. If the differential or integral equations are solved at each grid point, such solution is based on the strong form of the equations and the methods of getting such solution are called point collation methods, since solution between grid points are obtained by interpolation [19]. Finite difference (FD) method is a strong form solution based on differential equations, and the method of moments (MoM) (including the Brandt method [21-22]) is based on integral equations.

In contrast, in the weak form of the equations, the governing equations are multiplied by weighting functions and the integrated over the problem domain. A solution is obtained by minimising the weighted residuals so that the weighted errors over the whole domain is minimised. The domain is discretised into a mesh. Examples of methods that use the weak form of the equations are the finite element (FE) method, and the integration equation (IE) method.

The final class of method involves defining a functional that gives the total energy of the system, and one such method is the minimum electromagnetic entropy production (MEMEP) method [23]. The domain is also discretised into a mesh under the methods involving the minimization of an energy functional.

Each method exhibits distinct characteristics based on its discretization strategy and mathematical foundation. Among these, the FEM stands out in industrial applications for its geometric flexibility and capability for multiphysics coupling. It demonstrates excellent performance in modeling complex geometries such as three-dimensional coil windings and composite superconducting structures, and is widely adopted by commercial software like COMSOL Multiphysics.

To address the specific demands of HTS electromagnetic simulations, multiple specialized formulations have been developed within the finite element framework, tailored to optimize discretization strategies and coupling mechanisms for the material's nonlinear and anisotropic properties:

The H formulation uses magnetic field intensity as the primary variable, simulating nonlinear resistance through the coupling of Faraday's law with the E-J power law [24-30]. In this approach, H is directly solved in superconducting regions, and current density is derived via $J = \nabla \times H$. Its ease of implementation has led to widespread adoption in commercial software like COMSOL. However, in high aspect ratio geometries, mesh refinement can significantly increase computational burden. By simulating thin HTS tape as infinitely thin object, the T-A formulation introduced below, is more efficient [31].

As a hybrid approach, the *T-A* formulation [32] combines the *T*-formulation (for superconducting regions) with the *A*-formulation (for superconducting and non-superconducting regions), accelerating convergence high aspect ratio structures by reducing degrees of freedom [33]. In the *T-A* formulation, the thickness dimension of the thin HTS tape is reduced to zero. However, *T-A* formulation for thick conductors has also been developed [34].

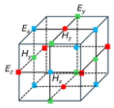
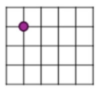
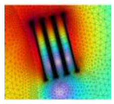
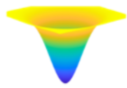
HTS modeling	Differential equations	Integral equations
Strong form of equations	 FD	 MoM
Weak form of equations	 FE	 IE
Minimization of functional	N/A	 MEMEP

Fig. 2. Numerical methods for HTS modelling.

4. HTS Applications

As listed in Table 1, major HTS applications include power transmission, electric machines, WPT, magnetic gears, superconducting magnetic energy storage (SMES), fusion reactors, magnetic resonance imaging (MRI), and some advanced systems.

4.1 Power Transmission and Fault Current Limiters

HTS cables represent a transformative advancement in power transmission technology, leveraging near-zero electrical resistance to achieve significantly higher efficiency and power density compared to conventional cables [35]. HTS cables can transmit bulk power with 5–9 times reduced size and weight while minimizing dielectric losses, making them ideal for space-constrained urban environments and high capacity grid expansions [36].

Two primary configurations dominate HTS cable applications: AC HTS cables and DC HTS cables. AC HTS cables currently dominate the market due to compatibility with existing AC grids and established technology [37]. However, they exhibit inherent AC losses under operational conditions. In contrast, DC HTS cables offer negligible dielectric losses, superior controllability for long-distance bulk power transmission, and enhanced suitability for renewable energy integration (e.g., solar/wind farms) [38]. Despite constituting small proportion of current projects, DC configurations are projected for exponential growth in interconnecting asynchronous grids and high-power applications [39].

Many HTS cable projects have already been implemented [40, 41]. However, critical challenges persist, including cryogenic maintenance and cost efficiency. Liquid nitrogen cryogen, while abundant and low-cost, risks asphyxiation if leaked. Triaxial cable designs reduce size but complicate repairs, increasing lifecycle costs. Economically, HTS cables also face the problem of high cost [42].

In addition, HTSs can be used as fault current limiters due to their low impedance in superconducting state, high impedance under fault-current condition, and ability to return to superconducting state after fault current clears [43, 44]. There has been a number of demonstration projects [43, 45], and HTS fault current limiters are one of the more mature electric power applications of superconductors.

4.2 Electric Machines

HTS electric machines [46] are a transformative technology offering exceptional power density and efficiency [47]. In terms of machine topology, designs are primarily based on the excitation method. HTSs can be used in field windings [48-50] or the armature [51]. Geometrically, machines are categorized by morphology: radial-flux designs [52]; axial-flux for compact, high-torque density [53, 54]; and linear configurations [55, 56].

In renewable energy, HTS machines enable lightweight, high-efficiency solutions. For wind power [57] and wave energy [58], they allow dramatic generator mass reduction [59-62]. For electric propulsion, the high torque of HTS machines is pivotal. Marine systems use multi-megawatt motors for low-speed, high-torque operation [63]. High power density HTS machines for future electric aircraft have also been investigated [64]. For electric vehicles [65], HTS motors achieve high torque density and efficiency, enabling direct-drive systems that eliminate gears and enhance performance [66]. HTS machines have also been proposed for flywheel energy storage [67].

4.3 Magnetic Gears

HTS magnetic gears leverage the unique properties of bulk HTS materials, particularly the Meissner effect, to achieve near-zero magnetic permeability and actively shape magnetic flux paths [68]. This enables non-contact torque or

Table 1. Overview of HTS Applications: Key Properties, Advantages, and Challenges

	Key HTS properties	Main advantages	Core technical challenges
Power transmission	• Zero resistance • High J_c	• High transmission capacity • Low losses • Compact size	• AC losses • Reliability of cryogenic systems • High initial investment
Electric machines	• High J_c • High H_c	• High power density • High efficiency • Compact designs	• AC losses • Integration of rotating cryogenic systems • Material brittleness • Harmonic suppression
Magnetic gears	• Meissner effect	• Non-contact operation • High torque density • Maintenance-free	• Requirement for integrated, continuous, reliable cryogenic systems
Wireless power transfer	• Low loss • High J_c	• High power density • High efficiency	• AC losses • Cost/reliability of cryogenic systems
Magnetic energy storage	• Zero resistance • High J_c	• Fast response • High round-trip efficiency • Long lifespan	• AC losses • Magnet stability • Thermal leakage from current leads
Fusion reactors	• High J_c	• High magnetic fields • Compact designs	• Resistance to high-energy neutron radiation damage • Management of nuclear heating
Magnetic resonance imaging	• High H_c • High temperature operation	• Reduction of cooling cost • Ultra-high-field whole-body systems	• High material cost • Quench protection challenges
Particle accelerators	• High H_c • High J_c	• Compact designs	• Radiation hardness • Thermal management under nuclear heating • Material activation and lifetime reliability
Precision measurement	• Josephson effect • Meissner effect	• High measurement accuracy	• Complex equipment • Requirement for cryogenic environment • High demand for material homogeneity
Quantum computing	• Zero resistance • Josephson effect	• Basis for superconducting qubits	• Material defects affecting qubit coherence times • Complex large-scale 3D integration processes

force transmission with significantly higher power density, reduced acoustic noise, inherent overload protection, and maintenance-free operation compared to mechanical gears or traditional magnetic gears. The shielding property of HTS bulks has also been used in a proposed vernier machine [69].

Regarding HTS magnetic gears, scholar have proposed various configurations. In coaxial magnetic gears, bulk HTS materials replace ferromagnetic segments in the stationary ring [70]. This substitution not only achieves effective magnetic field modulation but also suppresses end-effects common in traditional designs. Since bulk HTS materials can actively modulate magnetic flux without ferromagnetic materials, the stationary ring can achieve a radially compact design. In tubular linear magnetic gears, bulk HTS materials are used for magnetic field modulation in linear motion applications [71]. HTS blocks are inserted between ferromagnetic rings in a "zebra-striped" configuration to minimize flux leakage. Analytical models confirm that the ideal zero permeability characteristic of HTS maximizes the fundamental harmonic of magnetic permeance, thereby directly enhancing thrust force.

Despite the compelling advantages, the cost of HTS materials themselves and the need for sophisticated electromagnetic and thermal design pose considerable challenges. Research so far is predominantly at the simulation stage, necessitating further experimental validation and long-term reliability studies to transition this promising technology from the laboratory to practical industrial applications.

4.4 Wireless Power Transfer (WPT)

HTS WPT [72] utilizes HTS materials to overcome the limitations of conventional copper-based systems. Its fundamental advantage stems from the exceptionally low AC resistance of HTS coils, which results in a quality factor (Q-factor) significantly higher than that of conventional copper coils [73]. The high Q-factor leads to high efficiency. In addition, the large current density carried by HTS allows high power density of the WPT system, which is particularly advantageous to wirelessly charge electric drones while flying [74].

It should be noted, however, that practical challenges—including AC losses in HTS windings and cryogenic cooling requirements—must be addressed to fully realize these theoretical benefits [75]. Therefore, while HTS WPT holds significant potential for achieving high efficiency, high power, and high power density, its overall performance is concomitantly governed by these practical engineering considerations [76].

A critical challenge is AC loss in HTS materials under high-frequency operation, which generates heat and necessitates power-intensive cooling (e.g., liquid nitrogen) [77]. This cooling overhead can offset efficiency gains, particularly in high-frequency systems. Consequently, research prioritizes low-frequency (LF), high-power designs, where AC losses are minimized.

By integrating WPT with electric machines, a new family of wireless machines has been actively developed [78]. With the use of HTS materials, these wireless machines have high potential to work in remote, isolated environment [79].

4.5 Superconducting Magnetic Energy Storage (SMES)

SMES stores energy in the magnetic field generated by DC flowing through an HTS coil, leveraging near-zero resistance to achieve high efficiency and minimal energy loss during extended operation. This system provides millisecond-level rapid response capabilities, making it suitable for grid stabilization, load-leveling, and power quality improvement in distributed generation systems [80, 81]. Grid stabilization using SMES over multiple hours has also been investigated [82]. Optimization efforts focus on minimizing HTS tape consumption and reducing von-Mises stress in coil design.

A critical challenge for HTS energy storage systems – especially SMES magnets – lies in maintaining the superconducting state. Flux creep under external magnetic fields causes current decay in HTS magnets, necessitating continuous external power supply [83]. Traditional current leads bridging ambient and cryogenic environments introduce significant thermal leakage, increasing cooling costs and quenching risks. HTS WPT technology offers a promising solution by enabling contactless energy transmission to HTS magnets within cryogenic environments, thereby eliminating physical current leads and associated thermal losses.

Despite these advantages, AC losses in HTS coils – influenced by magnetic field strength, coil structure, HTS material properties, current amplitude, and frequency – constitute a major constraint on overall system efficiency [84].

4.6 Magnetic Resonance Imaging (MRI)

HTS technology is pivotal for the development of next-generation high-field MRI systems. These systems utilize superconducting magnets to generate a powerful and stable static magnetic field, with the main magnet playing the critical role of providing the essential environment for the magnetic resonance of hydrogen nuclei within the human body [85]. HTS magnets' ability to break the magnetic field strength limits of traditional LTS materials is revolutionary, as it enables clinical and research MRI systems to achieve unprecedented ultra-high field strengths [86].

However, the stringent requirements for extreme magnetic field homogeneity and long-term stability in MRI systems present unique engineering challenges for HTS magnets [87]. Current fluctuations, mechanical stress, or thermal disturbances can trigger local instabilities in the superconducting state, potentially leading to a "quench" which can damage the superconducting magnet itself [88]. The complex winding structures and extremely high current densities further exacerbate the difficulty and potential risks of quench protection [89]. The resulting instantaneous overheating and tremendous electromagnetic stresses impose more stringent requirements on the magnet's real-time quench detection [90].

4.7 Particle Accelerators

HTSs are pivotal for next-generation particle accelerators. These machines utilize electromagnetic fields to propel charged particles to near-light speeds, with dipole magnets playing the critical role of bending the particle beam along a circular path [91]. HTS magnets' ability to generate extremely high magnetic fields is revolutionary, as it enables significantly more compact accelerator rings [92]. This directly translates to reductions in both the physical footprint and the overall cost of future colliders and synchrotrons compared to conventional designs.

However, the high-energy particle beam environment in accelerators presents severe radiation challenges [93]. Protons and electrons generated from beam losses or collisions directly threaten the integrity of HTS magnets, causing ionization and displacement damage [94]. The resulting heat deposition effects impose stricter requirements on thermal management and quench protection of the magnets [95]. Therefore, optimizing radiation shielding and thermal management strategies is crucial for ensuring the reliable operation of HTS magnets throughout the entire lifespan of an accelerator.

4.8 Fusion Reactors

HTSs are pivotal for compact fusion reactors due to their ability to generate magnetic fields exceeding 20 T, enabling significant reductions in reactor size and cost compared to conventional designs [96]. It is possible for HTS to generate high magnetic fields in fusion reactors because of HTS materials' superior current-carrying capacity under intense magnetic fields and zero-resistance characteristics.

However, the compact design intensifies radiation challenges. Neutrons and secondary particles from fusion reactions threaten HTS magnet longevity, particularly Rare-Earth Barium Copper Oxide (REBCO) tapes like YBCO, which face degradation from displacement damage and thermal loads [94, 97]. Secondary particles (photons, protons) further contribute to localized damage, particularly in unshielded configurations.

4.9 Precision Measurement

Superconductors offer transformative advantages in precision measurement by leveraging unique macroscopic quantum phenomena, to achieve accuracy beyond conventional technologies. The Josephson effect, for instance, enables quantum voltage standards where Josephson junctions under microwave irradiation produce a quantized DC voltage $V=n(h/2e)f$ (where n is an integer, h is Planck's constant, e is the electron charge, and f is frequency). This relationship, dependent solely on fundamental constants, eliminates reliance on physical artifacts [98]. Josephson voltage standards can be used for high precision voltage measurement [99].

The SQUID is also based on Josephson junctions, with a fundamental structure consisting of a superconducting loop containing two Josephson junctions [100, 101]. When a weak external magnetic field passes through the loop, it induces quantized changes in the supercurrent. By measuring the periodic variations in the current or voltage within the loop, the corresponding magnetic flux change can be deduced with high precision, enabling accurate determination of the original magnetic field strength.

The superconducting nanowire single-photon detector (SNSPD) employs an extremely thin superconducting nanowire as its core sensing element. When a single photon strikes the nanowire, the device can generate a detectable electrical pulse with high probability, enabling highly efficient single-photon detection [102].

4.10 Quantum computing

Quantum computing systems must operate at cryogenic temperatures to maintain qubit coherence and minimize thermal noise [103]. The currently dominant superconducting quantum computing architecture employs superconducting qubits as the basic information units, which function at millikelvin ultralow temperatures [104]. The implementation of such qubits is based on superconducting circuits containing Josephson junctions, utilizing their macroscopic quantum effects at low temperatures to encode and manipulate quantum states [105]. Although this represents one of the most mature and scalable approaches available, it still faces significant challenges, particularly limited coherence times and high susceptibility to decoherence caused by electromagnetic noise, material defects, and other factors [106].

A major bottleneck in scaling up the system lies not only in the performance of the qubits themselves but also in the efficient interconnect between the quantum processor and the classical control electronics, which requires establishing low-loss, high-density electrical signal pathways within the cryogenic environment [107, 108].

5. Outlook

Much is expected to happen in development of superconductor applications. In the short term (0-5 years), superconducting cables are expected to become more mature, with projects like SuperLink (110kV, 500 MVA, 15 km) in Munich under continual development. Many fusion companies have aggressive timelines. For example, the SPARC reactor by Commonwealth Fusion Systems (CFS), which uses HTS magnets, is expected to achieve net energy generation (Q>1) in 2027. The commercial power generator by CFS, the ARC reactor, is expected to be operational in the 2030s. These HTS function reactors demand long lengths of HTS cables and are expected to drive the cost of HTS cables down as production of HTS tapes expands, thus enabling other applications of HTSs where cost of HTSs would otherwise be a limiting factor. In the medium term (5-15 years), superconducting machines may become ready for deployment. For example, part of the Japanese LTS maglev train Chūō Shinkansen is expected to enter service. Superconducting machines for aviation are expected to become mature, although due to regulatory assessment, fully electric passenger planes employing superconducting machines may take longer (beyond 2040) to enter service. In the long term (15+ years), commercial fusion may become mature and thus revolutionize the way electricity is generated. In addition, quantum computing with superconducting qubits, after overcoming challenges with scalability and quantum error correction (QEC), may be equipped with millions of qubits with QEC and thus revolutionize future scientific discoveries, cryptography and artificial intelligence. Similar to the trajectory of other technologies, superconductor technologies will soon be translated into education [109, 110].

6. Conclusion

HTS materials are a pivotal technology with revolutionary potential, enabled by their unique high critical parameters. These properties underpin transformative applications like efficient power transmission, compact high-density electric machines, and the intense magnetic fields needed for fusion and quantum computing. However, widespread commercialization faces challenges, including material brittleness, AC losses, and the cost and complexity of cryogenic systems. Overcoming these hurdles requires advances in more ductile, cost-effective wires and simpler cooling solutions. By successfully addressing these limitations, HTS technology is poised to play a central role in next-generation power generation, transportation, sensing and computing.

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Rui Lyu
Rui Lyu received the B.Sc. degree in Electrical Engineering from China University of Mining and Technology, Beijing, China, in 2020, and the M.Sc. degree in Electrical Engineering from Tianjin University, Tianjin, China, in 2023. He is currently pursuing the Ph.D. degree in Electrical Engineering at the University of Hong Kong, Hong Kong SAR, China. His research interest focuses primarily on wireless power transfer.

Calvin C. T. CHOW
Calvin C. T. Chow received the B.A. and M.Eng. degrees in engineering from the University of Cambridge, Cambridge, U.K., both in 2020, with specialization in areas including control and information engineering. He is currently pursuing the Ph.D. degree in electrical and electronic engineering with the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong, SAR, China.,His research interests include superconducting machines and drives, transportation electrification, and electric vehicle technologies.

Wei Liu
He (IEEE Senior Member) received the B.Eng. and M.Eng. degrees in electrical engineering from China University of Petroleum, Qingdao, China, and a Ph.D. degree in electrical and electronic engineering from The University of Hong Kong (HKU), Hong Kong, China, in 2014, 2017, and 2021, respectively.

He is currently an Assistant Professor at the Research Centre for Electric Vehicles and Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University (PolyU). He has also been an Honorary Assistant Professor at the Department of Electrical and Electronic Engineering, HKU, since 2023. Dr. Liu served as a Postdoctoral Fellow and was then promoted to a Research Assistant Professor from 2021 to 2023. He also worked as a Visiting Researcher with Nanyang Technological University, Singapore (NTU), in 2019. His research interests include electric vehicle technologies, wireless power transfer, power electronics, bioelectronics, and semiconductor devices.

Dr. Liu was the recipient of the Power Engineering Prize from HKU, two Gold Medals with Congratulations of the Jury in the International Exhibition of Inventions Geneva, the Excellent Paper Award, and the Best Presentation Award from international conferences in the area of Electric Vehicles and Transportation Electrification. He is also a Guest Associate Editor of the IEEE Journal of Emerging and Selected Topics in Power Electronics (JESTPE), Associate Editor of international journals, and Session Chair of international conferences.

Yunhe Hou
He (IEEE Fellow) received the B.E. and Ph.D. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 1999 and 2005, respectively. He was a Postdoctoral Research Fellow with Tsinghua University, Beijing, China, from 2005 to 2007, and a Postdoctoral Researcher with Iowa State University, Ames, IA, USA, and the University College Dublin, Dublin, Ireland, from 2008 to 2009. He was also a Visiting Scientist with the Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, MA, USA, in 2010. He has been a Guest Professor with the Huazhong University of Science and Technology, China, since 2017, and an Academic Adviser of China Electric Power Research Institute since 2019. He joined as a Faculty with the

University of Hong Kong, Hong Kong, in 2009, where he is an Associate Professor in the Department of Electrical and Electronic Engineering. He was an Associate Editor of IEEE TRANSACTIONS ON SMART GRID from 2016 to 2021. He is currently an Associate Editor of IEEE TRANSACTIONS ON POWER SYSTEMS and the Journal of Modern Power Systems and Clean Energy.

C. C. Chan
He (IEEE Life Fellow) was born in 1937. He received the B.S. degree from the China University of Mining and Technology, Xuzhou, China, in 1957, the M.S. degree from Tsinghua University, Beijing, China, in 1959, and the Ph.D. degree from The University of Hong Kong, Hong Kong, in 1982, respectively, all in electrical engineering.

He has more than 50 years of teaching and research experience and proposes engineering philosophy, engineering, and education innovation, which laid the foundation of modern electric vehicles theory and electric vehicles electric drive theory. He has authored more than 300 papers and 11 monographs.

Dr. Chan is a Member of the Chinese Academy of Engineering, a Fellow of the Royal Academy of Engineering, U.K., a Member of the Ukrainian Academy of Engineering Sciences, and an Honorary Fellow of the Hungarian Academy of Engineering. He is a Senior IET Fellow and the former President of the Hong Kong Institution of Engineers. He was the recipient of the Toastmasters Medal from the Institution of Electrical Engineers (IEE)in 2000, named "Father of Asian Electric Vehicles" by Magazine Global View in 2003, and he received the Environmental Excellence in Transportation Award from the Society of Automotive Engineers (SAE) in 2007, Gold Medal of Hong Kong Institution of Engineers in 2010, World Federation of Engineering (WFEO) Medal for Engineering Excellence in 2013, Prince Philip Medal of U.K. Royal Academy of Engineering in 2014, and the IEEE Transportation Technologies Award from the Institute of Electrical and Electronics Engineers (IEEE) in 2018.

K. T. Chau
He (IEEE Fellow) received the B.Sc. (Eng.), M.Phil., and Ph.D. degrees in electrical and electronic engineering from The University of Hong Kong, Hong Kong, in 1988, 1991, and 1993, respectively. Currently, he serves as Chair Professor of Electrical Energy Engineering at the Department of Electrical and Electronic Engineering and Co-Director at the Research Centre for Electric Vehicles, The Hong Kong Polytechnic University. His research interests include electric and hybrid vehicles, power electronics and drives, and renewable energies. He is the author of nine books and more than 400 journal papers.

Prof. Chau is a Fellow of the Institution of Engineering and Technology (IET), of the Hong Kong Institution of Engineers, and of the International Artificial Intelligence Industry Alliance. He is also a Chartered Engineer. He was the recipient of the Changjiang Chair Professorship from the Ministry of Education, China, and the Environmental Excellence in Transportation Award for Education, Training, and Public Awareness from the Society of Automotive Engineers International.