ICEE Conference 2024: TRANSformative Electrical Engineering for Future Society: The International Council on Electrical Engineering, June 30 - July 4, 2024. Kitakyushu International Conference Center, Kitakyushu, Japan

Design and Control of Wireless Electric Vehicle Direct Charging for Multistorey Car Parks

Wei Liu and K.T. Chau
Research Centre for Electric Vehicles and Department of Electrical and Electronic Engineering
The Hong Kong Polytechnic University, Hong Kong, China

Abstract

The popularization of electric vehicles (EVs) will bring a sustainable green-tech revolution to the world at large. Multistorey car parks (MCPs) will be one of the most potential solutions to advance transportation and urbanization toward electrification, connection, and intelligence, promoting the approach of carbon neutrality and sustainable development goals. Wireless charging technologies link the EVs and MCPs to interact with the power grid and renewable energy networks. Societal expectations of low carbon footprint and high space utilization will make requests for higher energy efficiency and higher power density of EV wireless chargers. Therefore, wireless direct charging (WDC) technology is developed to occupy less space and improve power conversion efficiency, thus conforming to societal expectations, especially for the MCPs in urban areas. Technically, a one-stage WDC is artfully devised to avoid the need for two-stage lossy power conversion during EV wireless charging. On top of the WDC topology, transmitter-end power control incorporated with new pulse frequency modulation (PFM) is proposed for automatic EV wireless charging. This control method can also be readily extended to bilateral power control using PFM for EV bidirectional charging, enabling wireless energy routing in the MCPs and wireless energy trading among EVs. Finally, theoretical analysis and computational simulation are given to verify the feasibility of the proposed WDC in urban MCPs.

Keywords: Electric vehicles, multistorey car parks, wireless direct charging, bidirectional charging, pulse frequency modulation

1 Introduction

Development of electric vehicles (EVs) [1], [2] will bring green and sustainable solutions for transportation electrification and decarbonization. With the development of artificial intelligence, communication technologies and self-driving technologies [3], modern EVs will evolve into intelligent mobile offices. Hodiernal millions of EVs and future billions of EVs create new demands for multistorey car parks (MCPs) having wireless charging capabilities [4]-[6]. Apart from wireless charging functions, the MCPs are expected to support bidirectional charging [7], [8] and wireless energy trading [9], [10] among EVs as well as wireless energy routing [11], [12] inside the MCPs.

Wireless charging technology provides us with a smart power interface [13], [14] between the power sources such as the power grid or renewable energy networks and electric loads such as EVs or MCPs. Furthermore, this wireless power transfer technology has been widely explored in numerous areas including multi-frequency power transmission [15]-[17], wireless motor [18], [19], wireless lighting [20], [21], magnetic field beamforming and editing [22], [23], wireless peer-to-peer charging [24], wireless energy encryption and decryption [25], [26], and wireless power and drive transfer [27], [28]. To control wireless power in various applications of wireless power transfer, multiple strategies have been actively developed for wireless energy modulation [5]. All these modulation strategies can be classified into five individual types plus one hybrid: (i) pulse width modulation such as duty ratio control and phase shift control [29], (ii) pulse density modulation [30], (iii) pulse frequency modulation (PFM) [31], [32], (iv) pulse phase/position modulation [33], (v) pulse amplitude modulation [34], and (vi) hybrid modulation [35]. In particular, the PFM exhibited the "real" merits, namely robust soft switching, eliminating even-order harmonics, alleviating switching loss, and lower switching frequency [36], [37].

Classified by different power flows, EV wireless charging and discharging typically have three types: (i) unidirectional grid-to-vehicle (G2V) charging [38], [39] (ii) bidirectional vehicle-to-grid (V2G) charging [40], [41], and (iii) bidirectional vehicle-to-vehicle (V2V) charging [42], [43], [10]. This paper is to investigate both the unidirectional and bidirectional wireless charging for EVs in MCPs. In urban area applications, MCPs should be deployed multifunctional wireless chargers for EVs, forming wireless energy internet by networking the parked EVs in the MCPs. To improve the space utilization and power conversion efficiency, wireless direct charging (WDC) technology using the PFM [32] can be developed to avoid the second-stage lossy power conversion [44] while adapting to different power sources and various requirements of battery management systems in EVs [45].

2 Multistorey Car Parks

Hodiernal millions of EVs will promisingly increase to billions of EVs in the near future, which highlights the charging demand and underlines the significance of charging convenience for EVs. In Fig. 1, wireless charging stations and MCPs can be constructed and deployed along the traffic roads in both the suburbs and urban areas. In particular, the development of MCPs incorporated with wireless chargers takes the definite advantage of improving space utilization for accommodating and charging more numerous EVs over the distributed wireless charging stations. Electricity can be fetched from the power grid on the ground and energy storage systems underground, and it can be converted into AC and DC forms while passing through the power electronic devices.

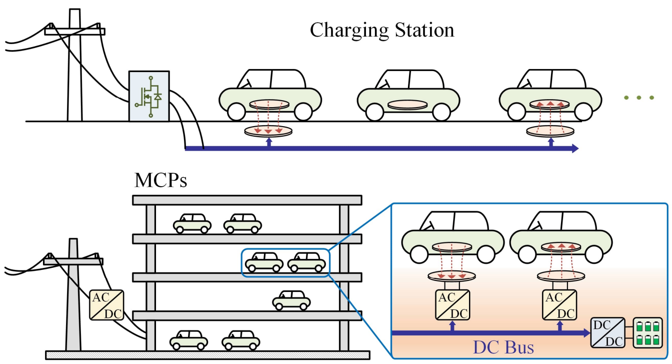

Fig. 1. Scenarios of wireless charging stations and MCPs.

Wireless charging behaviors can be classified into three types: (i) The batteries in EVs can be directly recharged via wireless chargers in the form of unidirectional power flow, coined as unidirectional G2V charging; (ii) EVs can discharge their batteries to feed electricity into the power grid or upload energy packets onto energy storage systems such as batteries [45], coined as bidirectional V2G operation; and (iii) the discharging EVs can directly charge another group of recharging EVs via wireless chargers, therefore routing the energy packets from the discharging EVs to the charging EVs. Meanwhile, the energy surplus and shortage can be balanced by the energy storage system and power grid via wireless energy routing and exchanging. This process can be coined as bidirectional V2V charging. Correspondingly, Fig. 2 shows the systematic configuration of wireless charging for EVs in MCPs or wireless charging stations. Multiple charging and discharging EVs are involved in energy exchange between themselves and power grids or energy storage systems.

3 Wireless Direct Charging

Fig. 3 shows the system topology of the proposed WDC for charging or discharging each EV in MCPs. In Fig. 4, only the switched power converter is controlled by double closed-loop proportional-integral (PI) controllers using the PFM to generate the required outputs, which guarantees to follow the references of constant-current (CC) and constant-voltage (CV) charging profile. This WDC avoids the use of second-stage DC-DC converters bilaterally, thus having the advantages of higher power conversion efficiency, higher power density, fewer components and lower cost. The proposed WDC benefits environmental friendliness and sustainability, reducing carbon footprint and promoting carbon neutrality.

For the 1st scenario of unidirectional G2V charging, Fig. 3(a) shows the circuit system of the proposed WDC system for unidirectional EV wireless charging. A low-cost diode rectifier can be used for directly charging the EV batteries, while all control is performed in the inverter at the transmitter side only. For the 2nd or 3rd scenarios of bidirectional V2G or V2V charging, Fig. 3(b) shows the circuit system of the proposed WDC for bidirectional (dis)charging the EVs wirelessly. Apart from functioning for the CC and CV charging, the PFM can also help the WDC to match different voltages of power sources and different specifications of power batteries.

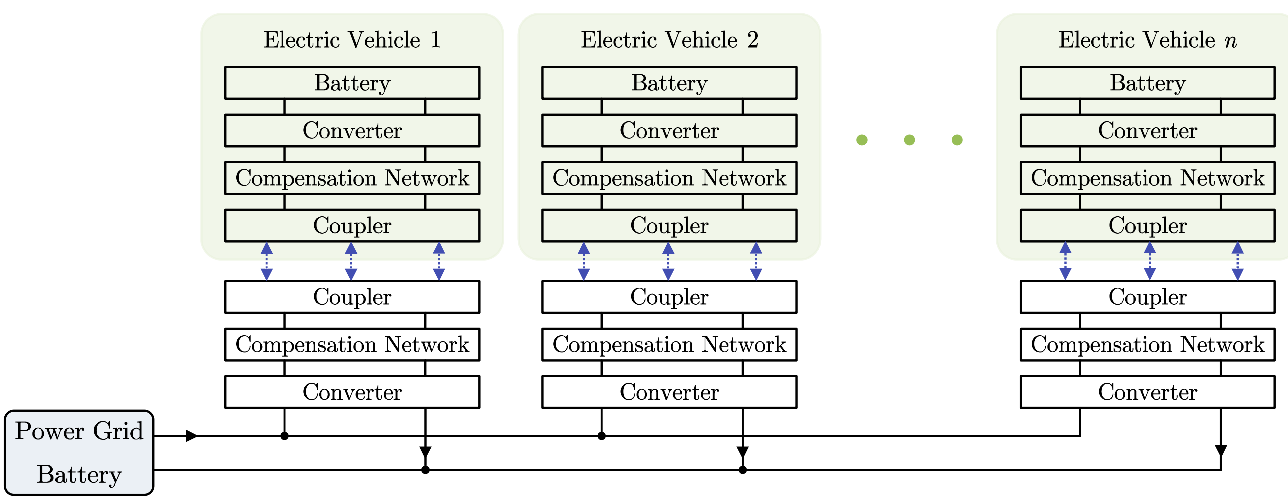

Fig. 2. System configuration of wireless charging for EVs in MCPs.

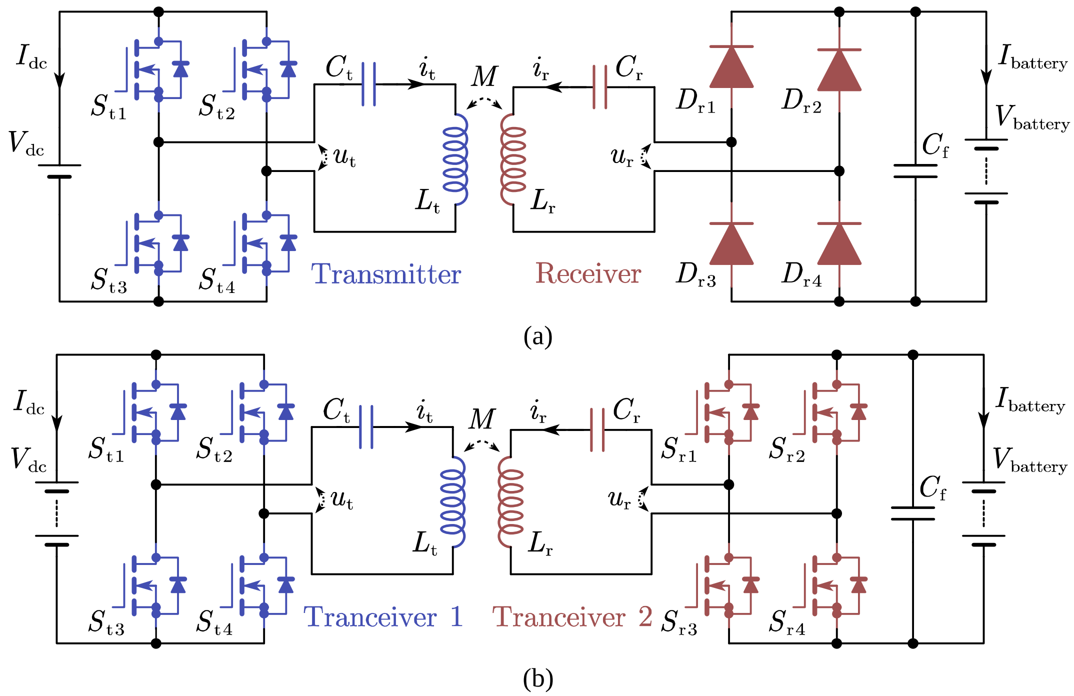

Fig. 3. Proposed WDC for EVs in MCPs. (a) Unidirectional G2V charging. (b) Bidirectional V2G or V2V charging.

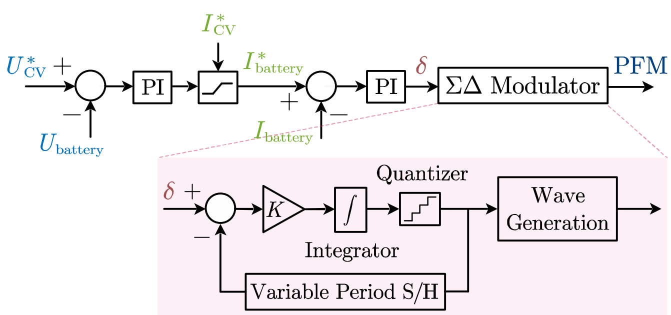

Fig. 4. Control algorithm using PFM for wireless charging.

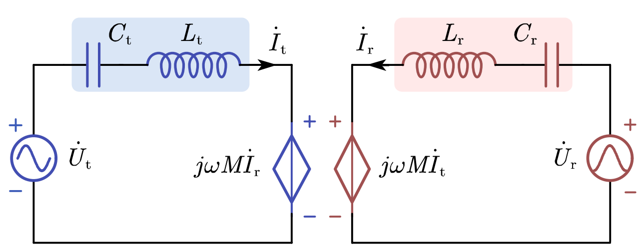

Fig. 5. Equivalent circuit of wireless charging for EVs.

Fig. 5 shows the equivalent circuit of the proposed WDC. A basic series–series network is used, which should follow:

$$\omega_0 = \frac{1}{\sqrt{L_t C_t}} = \frac{1}{\sqrt{L_r C_r}} \tag{1}$$

where ω_0 is the angular frequency; L_t and C_t are the coil inductor and matched capacitor of the transmitter (or transceiver 1); and L_r and C_r are those of the receiver (or transceiver 2). Besides, other types of basic and high-order networks can also be used for this WDC. For both the unidirectional and bidirectional WDC, the wireless power and its transmission direction can be controlled as given by [46]:

$$P = \frac{U_t U_r \sin\theta_{tr}}{\omega_0 M} \tag{2}$$

where U_t and U_r are the root-mean-square (RMS) values of transmitter and receiver (or transceiver) AC voltages, respectively; θ_{tr} is the phase difference between voltage phasors $\dot{U}_t$ and $\dot{U}_r$; and M is the mutual inductance of wireless charging coupler. Accordingly, $\theta_{tr} = \pi/2$ can control the forward transmission of wireless power from the power grid, energy storage system or discharging EVs to the charging EVs, and $\theta_{tr} = -\pi/2$ can control the reverse transmission of wireless power.

4 Wireless Charging Using Pulse Frequency Modulation

In Fig. 4, the sigma-delta (ΣΔ) modulation algorithm is borrowed to generate the PFM sequence [31], [47]. This PFM is in charge of CC/CV charging and voltage compatibility while achieving zero voltage switching, thus improving the system efficiency. No matter for unidirectional G2V charging or bidirectional V2G and V2V charging, the inverter output voltage using the PFM can be expressed as [46]:

$$u_{\mathrm{PFM}}(t)=\frac{1}{\delta_{\mathrm{d}}n_1+(1-\delta_{\mathrm{d}})n_2}\frac{4E}{\pi}\sin(\omega_0 t) \tag{3}$$

where $n_1=2n-1$ and $n_2=2n+1$; E is the DC voltage of inverter, namely V_{dc} or V_{battery}; and δ_{d} is the duty ratio of PFM. Moreover, δ is the ratio of the voltage RMS value $U_{\mathrm{PFM}}=U_{\mathrm{t}}$ and the current RMS value $I_{\mathrm{PFM}}=I_{\mathrm{t}}$ to their rated values U_{rated} and I_{rated}, respectively. Thus, it yields:

$$\delta=\frac{1}{\delta_{\mathrm{d}}n_1+(1-\delta_{\mathrm{d}})n_2} \tag{4}$$

$$U_{\mathrm{PFM}}=\delta U_{\mathrm{rated}},\quad I_{\mathrm{PFM}}=\delta I_{\mathrm{rated}} \tag{5}$$

5 Results and Verification

The specifications and parameters are listed in Table I to illustrate the design of the proposed WDC system in MCPs. In different scenarios, the DC voltage of power supply can be V_{dc} from the power grid and energy storage system or V_{battery} from the discharging batteries in EVs in Fig. 3. Both coil sizes of the coupler are in size of 420 mm×300 mm. A simulation model is built, and the computational simulation of two scenarios is performed to evaluate the feasibility and performance of the proposed WDC for EVs in MCPs. Due to the limitations of computing hardware, the battery capacity is scaled down by 10,000 times to speed up the simulation.

TABLE I
Design Specifications and Parameters of WDC System

	Parameter	Value
Transmitter (Transceiver 1)	Coil inductance (L_{t})	106.4 μH
	Coil internal resistance (R_{lt})	0.09 Ω
	Matched capacitance (C_{t})	32.95 nF
	Equivalent series resistance of C_{t} (R_{ct})	0.034 Ω
Receiver (Transceiver 2)	Coil inductances (L_{r})	104.6 μH
	Coil internal resistances (R_{lr})	0.07 Ω
	Matched capacitances (C_{r})	33.52 nF
	Equivalent series resistance of C_{r} (R_{cr})	0.034 Ω
	Coil turn (n_{r})	10
	Transfer distances (D)	150 mm
	Mutual inductances (M)	15.1 μH
	Nominal resonant frequency (f_0)	85.0 kHz
	DC input voltage (V_{dc})	350, 410 V
	EV battery voltage (V_{battery})	205 V

For the 1st scenario of unidirectional G2V charging, a synchronous rectifier, instead of a diode rectifier, is used at the receiver side to improve the system efficiency. When the PFM is used for the proposed WDC, Fig. 6(a) shows the waveforms of AC inputs (u_{t}, i_{t}) and outputs (u_{r}, i_{r}). By using a scaled-down battery to accelerate the simulation, the charging process can be shortened, which can show the whole charging profile for better visualization. With the scaled-down battery, Fig. 6(b) shows the whole charging process of EV batteries. When the battery voltage reaches 205.0 V, the charging control will switch from the CC mode of 26.0 A to the CV mode of 205.0 V. Fig. 6(c) shows the trends of output power and DC-to-DC system efficiency, where the maximum power is 5.329 kW, and the maximum system efficiency is 96.2%.

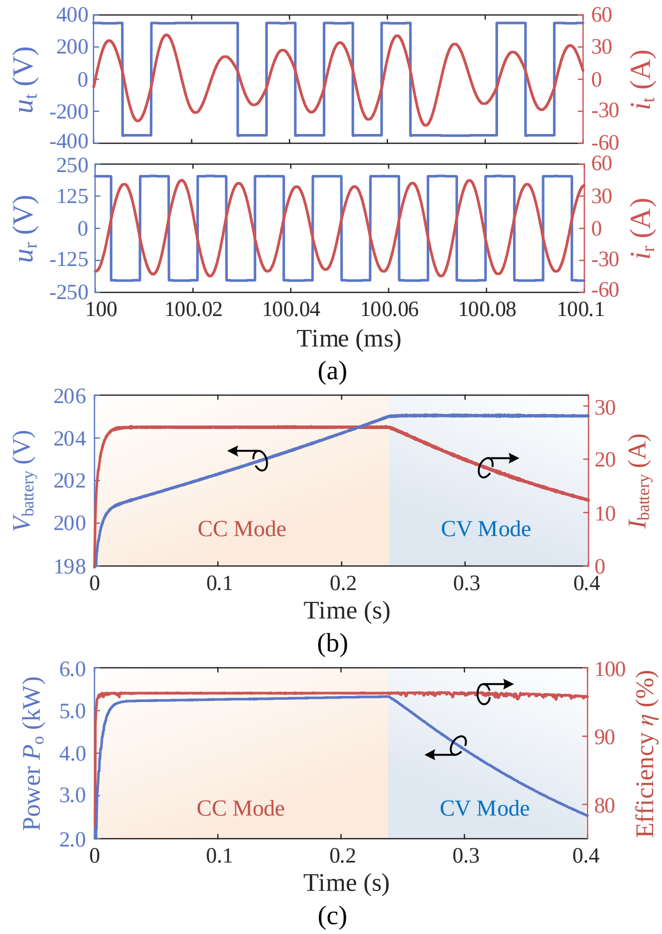

Fig. 6. Waveforms of unidirectional G2V charging. (a) AC inputs and outputs. (b) CC/CV charging (scaled-down battery for accelerating simulation). (c) Power and efficiency.

For the 2nd or 3rd scenario of bidirectional V2G or V2V charging, the PFM is also used for controlling the WDC. Accordingly, Fig. 7(a) shows the waveforms of AC inputs (u_{r}, i_{r}) and outputs (u_{t}, i_{t}). By using a scaled-down battery to accelerate the simulation, Fig. 7(b) shows the whole charging process of V2G or V2V operation. Similarly, when the battery voltage reaches 410.0 V, the charging control will switch from the CC mode of 13.0 A to the CV mode of 410.0 V. Fig. 7(c) shows the trends of output power and DC-to-DC system efficiency, where the power can reach 5.327 kW, and the system efficiency can reach up to 95.9%.

Therefore, the proposed WDC using the PFM can readily achieve high-efficiency G2V, V2G or V2V charging in the MCPs. All these results well verify the feasibility and high performance of the proposed WDC for EVs in the MCPs. This WDC scheme is very promising for urban applications.

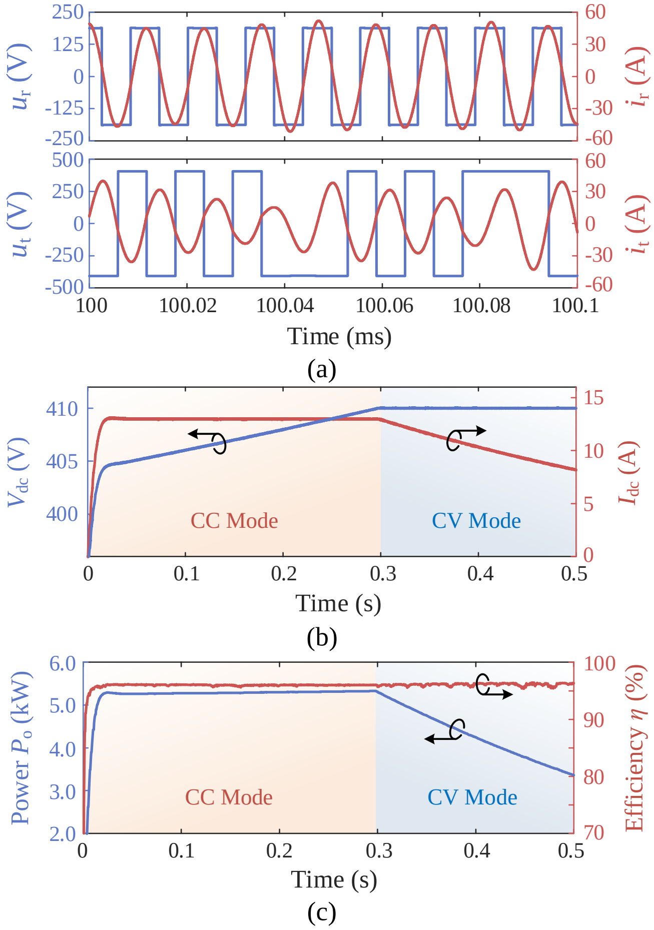

Fig. 7. Waveforms of bidirectional V2G or V2V charging. (a) AC inputs and outputs. (b) CC/CV charging (scaled-down battery for accelerating simulation). (c) Power and efficiency.

6 Conclusion

Ever-increasing EVs will advocate the development of MCPs having wireless charging capabilities, especially in urban areas. To promote the transportation and urbanization toward electrification, connection, and intelligence, the WDC technology using new PFM control has been proposed and evaluated for EVs in MCPs. To avoid the use of two-stage lossy power conversion, the proposed WDC has the advantages of high space utilization, high energy efficiency and high power density, which conforms to the societal expectations. On the other hand, transmitter-end power control incorporated with a new PFM can readily perform the automatic wireless charging for EVs in MCPs, successfully handling different scenarios of unidirectional G2V charging and bidirectional V2G or V2V charging. This control method can also be valid for wireless energy routing and wireless energy trading. Theoretical analysis and computational simulation have been given to verify the feasibility of the proposed WDC in urban MCPs.

Acknowledgment

This work was partially supported by a grant from the Hong Kong Research Grants Council, Hong Kong Special Administrative Region, China, under Project No. T23-701/20-R, and partially supported by two grants from The Hong Kong Polytechnic University, under Project No. P0048560 and P0048360. The authors thank Tianyi Liu for helping with the preparation of the figures and simulation.

References

[1] K.T. Chau, *Energy Systems for Electric and Hybrid Vehicles*. The IET, 2016.

[2] M. Ehsani, K.V. Singh, H.O. Bansal, and R.T. Mehrjardi, "State of the art and trends in electric and hybrid electric vehicles," *Proc. IEEE*, vol. 109, no. 6, pp. 967–984, Jun. 2021.

[3] M.D. Dean and K. Kockelman, "Our self-driving future will be shaped by policies of today," *Nat. Electron.*, vol. 5, no. 1, pp. 2–4, Jan. 2022.

[4] C.C. Mi, G. Buja, S.Y. Choi, and C.T. Rim, "Modern advances in wireless power transfer systems for roadway powered electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6533−6545, Oct. 2016.

[5] W. Liu, K.T. Chau, X. Tian, H. Wang, and Z. Hua, "Smart wireless power transfer — opportunities and challenges," *Renew. Sustain. Energy Rev.*, vol. 180, pp. 113298, Jul. 2023.

[6] W. Liu, K.T. Chau, C.H.T. Lee, C. Jiang, W. Han, and W.H. Lam, "Wireless energy-on-demand using magnetic quasi-resonant coupling," *IEEE Trans. Power Electron.*, vol. 35, no. 9, pp. 9057–9069, Sep. 2020.

[7] M. Huang, Y. Lu, and R.P. Martins, "A reconfigurable bidirectional wireless power transceiver for battery-to-battery wireless charging," *IEEE Trans. Power Electron.*, vol. 34, no. 8, pp. 7745–7753, Aug. 2019.

[8] J.Y. Lee and B.M. Han, "A bidirectional wireless power transfer EV charger using self-resonant PWM," *IEEE Trans. Power Electron.*, vol. 30, no. 4, pp. 1784–1787, Apr. 2015.

[9] D.H. Nguyen, "Electric vehicle — wireless charging-discharging lane decentralized peer-to-peer energy trading," *IEEE Access*, vol. 8, pp. 179616–179625, Sep. 2020.

[10] W. Liu, K.T. Chau, C.C.T. Chow, and C.H.T. Lee, "Wireless energy trading in traffic internet," *IEEE Trans. Power Electron.*, vol. 37, no. 4, pp. 4831–4841, Apr. 2022.

[11] H. Hua, J. Shi, X. Chen, *et al.*, "Carbon emission flow based energy routing strategy in energy internet," *IEEE Trans. Industr. Inform.*, vol. 20, no. 3, pp. 3974–3985, Mar. 2024.

[12] C.C.T. Chow, A.Y.S. Lam, W. Liu, and K.T. Chau, "Multi-source multi-destination optimal energy routing in static and time-varying vehicular energy network," *IEEE Internet Things J.*, vol. 9, no. 24, pp. 25487–25505, Dec. 2022.

[13] W. Liu, K.T. Chau, C.C.T. Chow, and C. Jiang, "Design and analysis of wireless electric vehicle energy network," *Proceedings of IEEE Transportation Electrification Conference and Expo, Asia-Pacific*, paper no. F0335, Haining, China, Oct. 2022.

[14] L. Yang, J. Huang, B. Feng, *et al.*, "Undersea wireless power and data transfer system with shared channel powered by marine renewable energy system," *IEEE J. Emerg. Sel. Top. Circuits Syst.*, vol. 12, no. 1, pp. 242–250, Mar. 2022.

[15] W. Liu, K.T. Chau, C.H.T. Lee, C. Jiang, W. Han, and W.H. Lam, "Multi-frequency multi-power one-to-many wireless power transfer system", *IEEE Trans. Magn.*, vol. 55, no. 7, pp. 8001609: 1–9, Jul. 2019.

[16] Z. Pantic, K. Lee, and S.M. Lukic, "Multifrequency inductive power transfer," *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 5995–6005, Nov. 2014.

[17] H. Pang, K.T. Chau, W. Liu, and X. Tian, "Multi-resonating-compensation for multi-channel multi-pickup wireless power transfer," *IEEE Trans. Magn.*, vol. 58, no. 8, pp. 8600506: 1–6, Aug. 2022.

[18] Z. Xue, K.T. Chau, W. Liu, and T.W. Ching, "Design, analysis, and implementation of wireless traveling-wave ultrasonic motors," *IEEE Trans. Power Electron.*, vol. 39, no. 4, pp. 4601–4611, Apr. 2024.

[19] Y. Xiao, Y. Yang, C. Liu, and J. Rodriguez, "Design and analysis of a wireless ultrasonic motor drive system," in *IEEE Trans. Power Electron.*, vol. 38, no. 10, pp. 12309–12314, Oct. 2023.

[20] W. Liu, K.T. Chau, C.H.T. Lee, C. Jiang, W. Han, and W.H. Lam, "A wireless dimmable lighting system using variable-power variable-frequency control," *IEEE Trans. Ind. Electron.*, vol. 67, no. 10, pp. 8392–8404, Oct. 2020.

[21] A. Kurs, A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, no. 5834, pp. 83–86, Jul. 2007.

[22] Y. Zhao, X. Li, Y. Ji, and C.Z. Xu, "Random energy beamforming for magnetic MIMO wireless power transfer system," *IEEE Internet Things J.*, vol. 7, no. 3, pp. 1773–1787, Mar. 2020.

[23] X. Tian, K.T. Chau, W. Liu, and C.H.T. Lee, "Selective wireless power transfer using magnetic field editing," *IEEE Trans. Power Electron.*, vol. 36, no. 3, pp. 2710–2719, Mar. 2021.

[24] O.N. Nezamuddin, C.L. Nicholas, and E.C.d. Santos, "The problem of electric vehicle charging: State-of-the-art and an innovative solution," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 5, pp. 4663–4673, May 2022.

[25] Z. Zhang, K.T. Chau, C. Qiu, and C. Liu, "Energy encryption for wireless power transfer," *IEEE Trans. Power Electron.*, vol. 30, no. 9, pp. 5237–5246, Sep. 2015.

[26] H. Wang, N. Tashakor, W. Jiang, W. Liu, C.Q. Jiang, and S.M. Goetz, "Hacking encrypted frequency-varying wireless power: cyber-security of dynamic charging," *IEEE Trans. Energy Convers.*, early access, 2024.

[27] W. Liu, K.T. Chau, C.H.T. Lee, L. Cao, and W. Han, "Wireless power and drive transfer for piping network," *IEEE Trans. Ind. Electron.*, vol. 69, no. 3, pp. 2345–2356, Mar. 2022.

[28] W. Liu, K.T. Chau, H. Wang, and T. Yang, "Long-range wireless power drive using magnetic extender," *IEEE Trans. Transport. Electrific.*, vol. 9, no. 1, pp. 1897–1909, Mar. 2023.

[29] Y. Jiang, L. Wang, Y. Wang, J. Liu, X. Li, and G. Ning, "Analysis, design, and implementation of accurate ZVS angle control for EV battery charging in wireless high-power transfer," *IEEE Trans. Ind. Electron*., vol. 66, no. 5, pp. 4075–4085, May 2019.

[30] H. Li, K. Wang, J. Fang, and Y. Tang, "Pulse density modulated ZVS full-bridge converters for wireless power transfer systems," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 369–377, Jan. 2019.

[31] R. Shinoda, K. Tomita, Y. Hasegawa, and H. Ishikuro, "Voltage-boosting wireless power delivery system with fast load tracker by ΔΣ-modulated sub-harmonic resonant switching," *IEEE International Solid-State Circuits Conference,* San Francisco, CA, USA, pp. 288-290, Feb. 2012.

[32] W. Liu, K.T. Chau, C.H.T. Lee, W. Han, X. Tian, and W.H. Lam, "Full-range soft-switching pulse frequency modulated wireless power transfer," *IEEE Trans. Power Electron.*, vol. 35, no. 6, pp. 6533–6547, Jun. 2020.

[33] K.P. Peppas, A.C. Boucouvalas, and Z. Ghassemloy, "Performance of underwater optical wireless communication with multi-pulse pulse-position modulation receivers and spatial diversity," *IET Optoelectron*, vol. 11, no. 5, pp. 180–185, Oct. 2017.

[34] P.L. Kamani and M.A. Mulla, "Middle-level SHE pulse-amplitude modulation for cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2828-2833, Mar. 2018.

[35] Z. Hua, K.T. Chau, W. Han, W. Liu, and T.W. Ching, "Output-controllable efficiency-optimized wireless power transfer using hybrid modulation," *IEEE Trans. Ind. Electron.*, vol. 69, no. 5, pp. 4627–4636, May 2022.

[36] X. Li, Y.P. Li, C.Y. Tsui, and W.H. Ki, "Wireless power transfer system with ΣΔ-modulated transmission power and fast load response for implantable medical devices," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 64, no. 3, pp. 279–283, Mar. 2017.

[37] W. Liu, K.T. Chau, C.H.T. Lee, X. Tian, and C. Jiang, "Hybrid frequency pacing for high-order transformed wireless power transfer," *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 1157–1170, Jan. 2021.

[38] Z. Hua, K.T. Chau, W. Liu, X. Tian, and H. Pang, "Autonomous pulse frequency modulation for wireless battery charging with zero-voltage switching," *IEEE Trans. Ind. Electron.*, vol. 70, no. 9, pp. 8959–8969, Sep. 2023.

[39] H. Pang, F. Xu, W. Liu, C.K. Tse, and K.T. Chau, "Impedance buffer-based reactance cancellation method for CLC-S compensated wireless power transfer," *IEEE Trans. Ind. Electron.*, early access, 2023.

[40] A. Triviño, I. Casaucao, and M. Castilla, "Flexible regulation of active and reactive power for a fully controllable V2G wireless charger," *IEEE Trans. Transp. Electrif.*, vol. 10, no. 1, pp. 1070–1079, Mar. 2024.

[41] M. Venkatesan, R. Narayanamoorthi, K.M. AboRas, and A. Emara, "Efficient bidirectional wireless power transfer system control using dual phase shift PWM technique for electric vehicle applications," *IEEE Access*, vol. 12, pp. 27739–27755, Feb. 2024.

[42] S. Taghizadeh, M.J. Hossain, N. Poursafar, J. Lu, and G. Konstantinou, "A multifunctional single-phase EV on-board charger with a new V2V charging assistance capability," *IEEE Access*, vol. 8, pp. 116812–116823, Jun. 2020.

[43] R. Xie, Y. Wu, H. Tang, Y. Zhuang, and Y. Zhang, "A strongly coupled vehicle-to-vehicle wireless charging system for emergency charging purposes with constant-current and constant-voltage charging capabilities," *IEEE Trans. Power Electron.*, vol. 39, no. 4, pp. 3985–3989, Apr. 2024.

[44] P. Zhao, G. Zheng, R. He, Y. Liu, and M. Fu, "A 45-W two-stage wireless fast charger using unregulated inductive power transfer," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 2, no. 3, pp. 287–296, Jul. 2021.

[45] W. Liu, T. Placke, and K.T. Chau, "Overview of batteries and battery management for electric vehicles," *Energy Reports*, vol. 8, pp. 4058–4084, Nov. 2022.

[46] S. Li and C.C. Mi, "Wireless power transfer for electric vehicle applications," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol.3 no.1, pp. 4–17, Mar. 2015.

[47] J. Guo, K.T. Chau, W. Liu, Z. Hua, and S. Li, "Segmented-vector pulse frequency modulated three-level converter for wireless power transfer," *IEEE Trans. Power Electron.*, to be published, 2024.

Contact E-mail Address: wei.liu@polyu.edu.hk; k.t.chau@polyu.edu.hk