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Bidirectional Wireless Charging for Electric Vehicle Network

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Executive Summary

Energy Internet is an emerging energy interconnection system, which links various types of energy networks to realize bidirectional power flow, peer-to-peer energy trading and energy packet sharing. In order to collaborate with other energy networks and accomplish effective energy asset management, bidirectional wireless charging over wireless energy routers (WERs) is proposed in a wireless electric vehicle (EV) energy network. The WERs are electrified as energy trading platforms to interact with EVs in such a way as to establish the distributed energy network nodes for bidirectional energy transmission with other network nodes. Both theoretical analysis and computational simulations are given to verify the feasibility of the proposed bidirectional wireless charging for the wireless EV energy network in various energy management scenarios.

Keywords: Energy Internet, bidirectional wireless charging, wireless energy router, electric vehicle.

1 Introduction

To deal with global energy demands and environmental crises, developing the global Energy Internet in a cleaner and greener way is an inevitable trend to realize the decoupling of economic development and carbon emissions [1], aiming for decarbonization. Recently, EV technologies have been attracting growing attention owing to their high energy efficiency and low pollution emissions [2]-[4]. With the capability and advantage of fully utilizing renewable energy, EV technologies are considered to have the potential to alleviate the global energy and environmental crisis effectively [5]-[7].

On the other hand, the importance of sustainability, safety and protection of the environment for energy utilization has received great attention [8]. With the diversity of the application scenarios of electrical appliances, the drawbacks brought by the traditional wired power supply method are gradually coming to the fore, such as easy wear and tear, the existence of leakage hazards and the tendency to produce contact sparks [9]. Therefore, wireless power transfer (WPT) technology with cleanliness, convenience and safety is gradually recognized [10]-[14]. As an emerging charging modality, wireless charging uses the high-frequency alternating magnetic field as the energy carrier to realize convenient and safe access to power supplies and solves the problems of electric sparks and complex maintenance existing in conventional power transmission modes [15]-[17].

Recently, WPT has shown great application potential in EVs [18], portable appliances [19], wireless lighting [20, 21], and biomedical implants [22]. For now, the range anxiety of EVs is mitigated by stacking the bulky battery pack, while WPT is a potential solution to alleviate the over-reliance of EVs on charging piles and batteries. Thanks to the rapid development of WPT technologies, both dynamic wireless charging technology and load-independent constant-current (CC) or constant-voltage (CV) charging technology have been developed for flexible EV charging [23, 24]. The resonant network has the transmission characteristics of CC or CV output at a specific frequency point, and the switching between CC and CV modes can be realized by adjusting the resonant frequency [25]. However, the time point of resonant frequency switching requires wireless communication between the primary and secondary sides, which inevitably increases the control complexity and hardware cost of the system. The phase shift control (PSC) can be utilized to regulate the output voltage of the inverter to ensure the CC and CV operation during the whole charging process, but the soft-switching condition of the inverter is difficult to be maintained except for using additional control schemes [26]. In addition, many efforts have been made to improve the efficiency of the system. The maximum power efficiency tracking method is achieved by the closed-loop control of a buck-boost converter on the secondary side of the WPT system [27]. The basic principle is to keep the equivalent load resistance of the secondary circuit at the optimal value, and the minimum power efficiency tracking can be achieved by searching for the minimum input power operating point. It should be noted that this method can be implemented without using any communication devices at the primary and secondary sides, but the maximum efficiency tracking process is slow. Additionally, the pulse frequency modulation (PFM) scheme for the WPT system is developed [28], which can effectively suppress switching frequency and switching loss and achieve a full-range soft-switching by alternating modulation of the WPT system at two different switching frequencies. Furthermore, a hybrid modulation WPT scheme combining PFM and on/off keying (OOK) modulation further improves the system efficiency by optimizing the load resistance [29]. In addition, some novel concepts and schemes have emerged to further promote the intelligent development of wireless charging for EVs, such as wireless energy trading [30], wireless energy routing [31, 32], multi-frequency WPT [33], magnetic field editing [34], wireless energy encryption [35], wireless induction heating [36], and wireless motors [37, 38].

In this paper, bidirectional wireless charging over WERs is proposed in the wireless EV energy networks, which can be utilized for cooperation and energy routing among multiple energy networks. By deploying the WER at each traffic node, mobile EVs can be wirelessly networked to route the energy flow in the wireless energy network via the proposed bidirectional wireless charging. Different EVs can achieve bidirectional wireless energy transmission through the WERs to achieve the optimal allocation and utilization of energy assets. Meanwhile, for gaining profits, bidirectional wireless charging can effectively support EVs to conduct wireless energy trading among peers over the same WERs.

The rest of this paper is organized as follows. Second II will discuss the topology and working principle of the bidirectional wireless charging electric vehicle network. In Section III, simulation results and analysis will be given to verify the effectiveness of the proposed bidirectional wireless charging system. Then the conclusion will be drawn in Section IV.

2 Methodology

EVs have grown rapidly in recent years due to their environmental friendliness, convenience and comfort. Nevertheless, insufficient battery capacity, slow charging speed, and the difficulty of installing charging infrastructure are the major bottlenecks restricting the development of EVs. Electrifying the transport network through WPT technology is a promising way to solve these problems. In the electrified transportation network, each road junction is configured WERs by deploying energy conversion and storage systems underground. Fig. 1 shows the typical configuration scenario of the electrified transportation networks, as the WERs are configured underground to interconnect with other energy network nodes and power grids, they will not affect transportation as well as road safety.

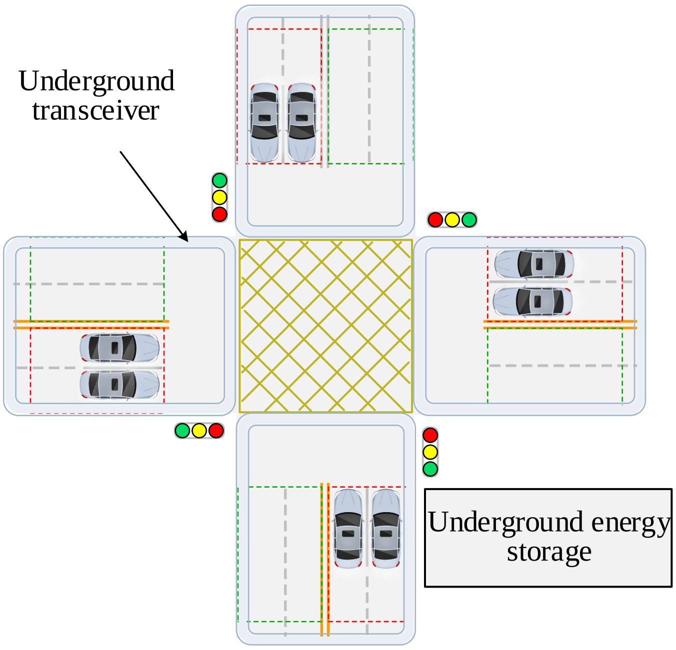
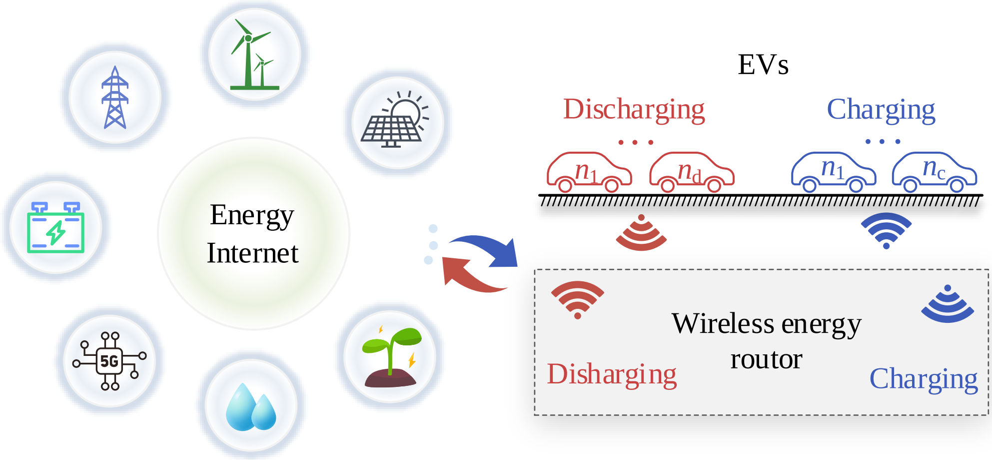
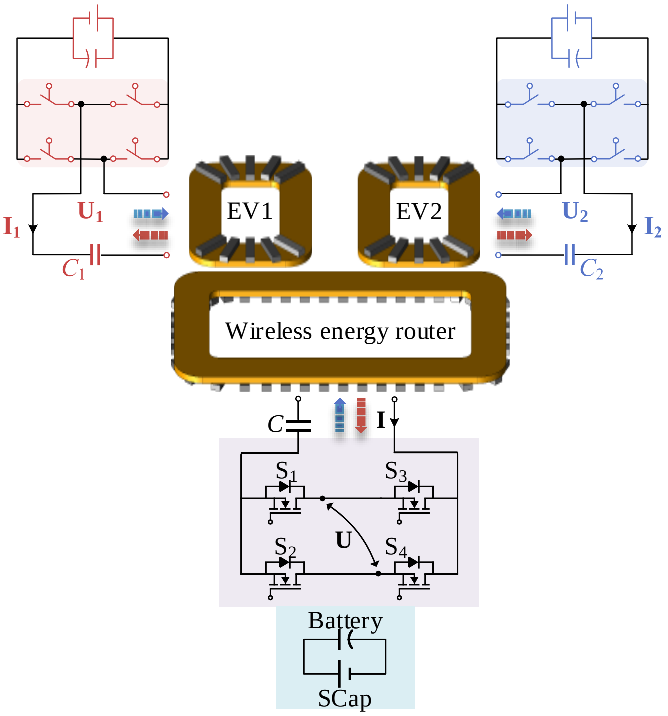


Figure 1: WERs configurated at the road junction.

Fig. 2(a) shows the schematic of the proposed bidirectional wireless charging over WERs in the wireless EV energy network. Each WER and EV includes a hybrid storage system for energy storage, a power converter for energy conversion, and a transceiver for energy transmission. As a key node, the WER plays an important role in the emerging wireless EV energy network. Not only can the electricity be wirelessly transmitted to the neighbouring EVs via the WER, but the surplus electricity can also be uploaded from EVs to the WER for energy storage. In addition, multiple EVs can carry out bidirectional wireless power transmission through one same WER for sharing, which brings great convenience to the wireless (dis)charging and energy management of EVs. Accordingly, the system configuration of one energy network node comprising one WER and two EVs is shown in Fig. 2(b). Typically, WER and EVs are configured with the same structure, but the energy storage system of WER is much large than that of EVs, as the energy flow between EVs and the power grid requires WER processing.



(a)

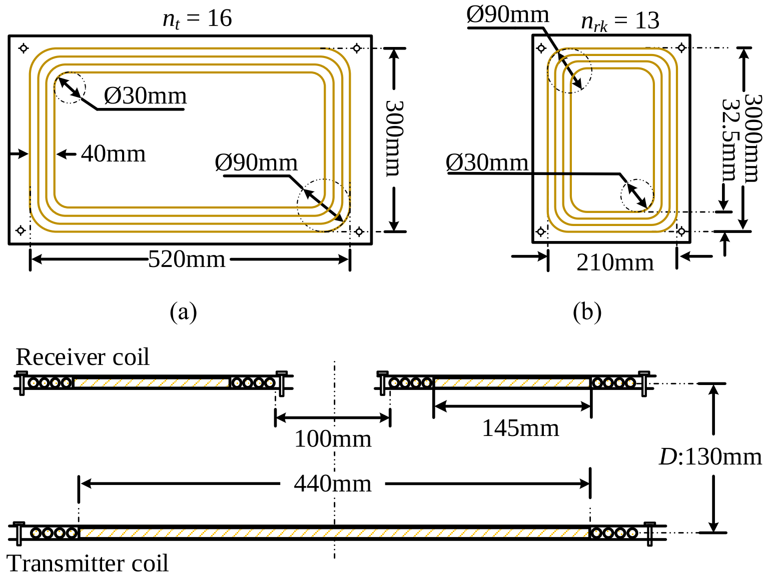


(b)

Figure 2: Proposed bidirectional wireless charging over WERs. (a) Schematic of wireless EV energy network. (b) System configuration of one network node comprising one WER and two EVs.

3 Results and Verification

To verify the proposed bidirectional wireless charging over WERs for wireless EV energy networks, three typical energy management scenarios are investigated: (1) Charging-discharging energy balance, (2) charging demand excess, and (3) discharging demand excess. In general, the transceiver of WER is installed under the intersection, while the transceivers of EVs are installed on the bottom of EVs. Fig. 3 shows the geometries of transceiver coils, and the design specifications and parameters for WER and EVs are listed in Table 1.



(a) (b)

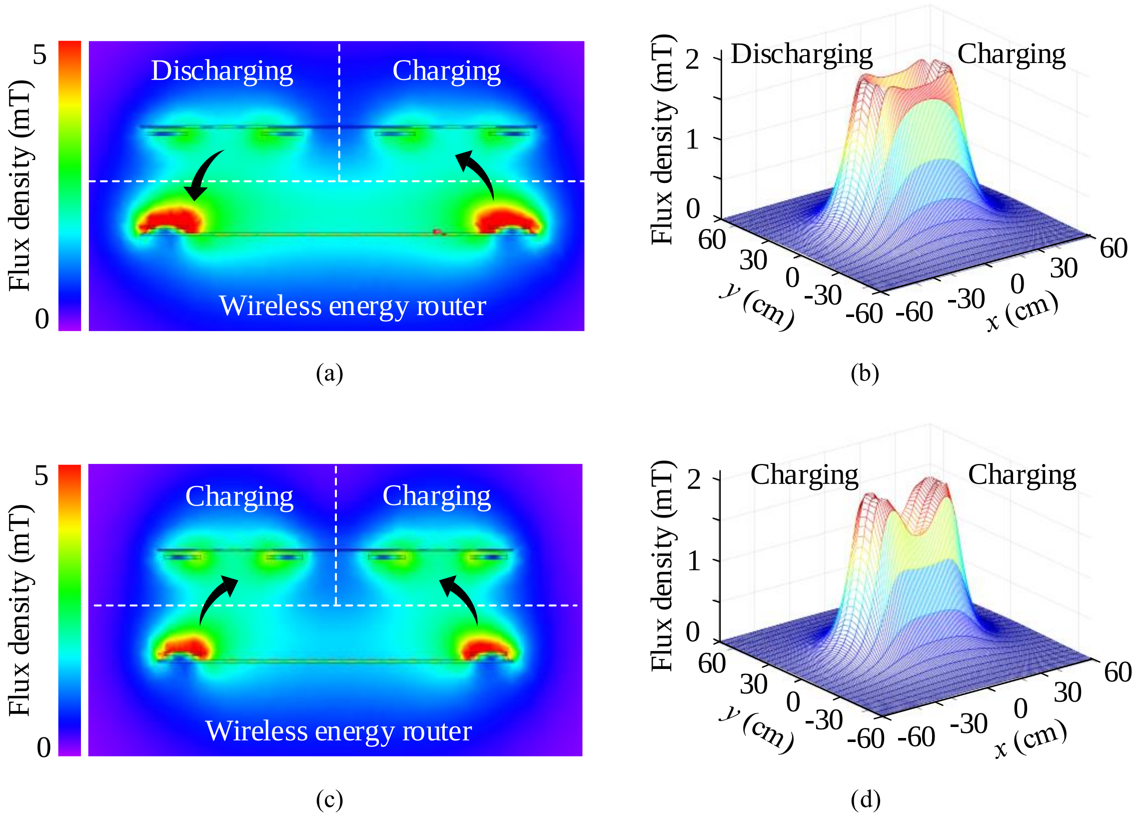
(c)

Figure 3: Geometries of transceiver coils. (a) Transceiver coil of WER. (b) Transceiver coil of EV. (c) Displacement among coils.

Table 1: Design specifications and parameters for WER and EVs

Items	Value
WER transceiver coil (L)	222.87 μH
Internal resistance of WER transceiver coil (R)	0.089 Ω
WER transceiver coil turns (n)	16
Resonant capacitance of WER coil (C)	15.73 nF
EV transceiver coils (L_n)	55.76, 55.73 μH
Internal resistances of EV transceiver coils (R_n)	0.045 Ω
EV transceiver coil turns (n_n)	13
Resonant capacitances of EV coils (C_n)	62.86, 62.91 nF
Mutual inductances (M_n)	11.08, 11.10 μH
Operating frequency (f)	85 kHz

The electromagnetic field distributions of three typical scenarios are simulated and assessed in Fig. 4 by using the finite element analysis (FEA). Fig. 4(a) shows the flux densities of one EV discharging and the other EV charging, where the WER serves energy forwarding. The three-dimensional (3-D) flux density along the intermediate plane between the EVs and the WER in this scenario is shown in Fig. 4(b). The magnetic field distribution of the charging EV is basically the same as that of the discharging EV, indicating that WER operates in forwarding mode without storing and releasing energy in this energy scenario. Then, Fig. 4(c) and Fig. 4(e) show the flux densities of two EV charging and two EV discharging, where the WER interacts with EVs by discharging and charging its energy storage system, respectively. Similarly, Fig. 4(d) and Fig. 4(f) demonstrate the 3-D flux density between EVs and WER along the intermediate plane in both scenarios, respectively. Discharging EVs can wirelessly transfer surplus energy to WER for storage, and also WER can transfer the stored energy to power-starved EVs for charging, thus enabling efficient energy flow and management.

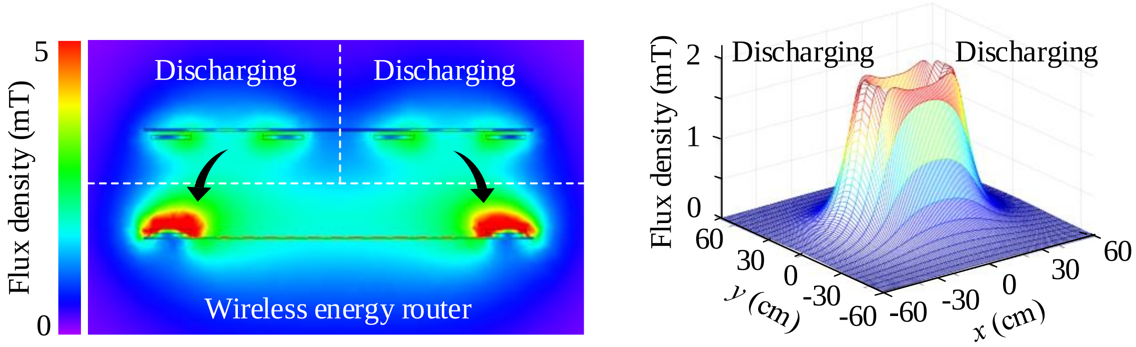


(a)

(b)

(c)

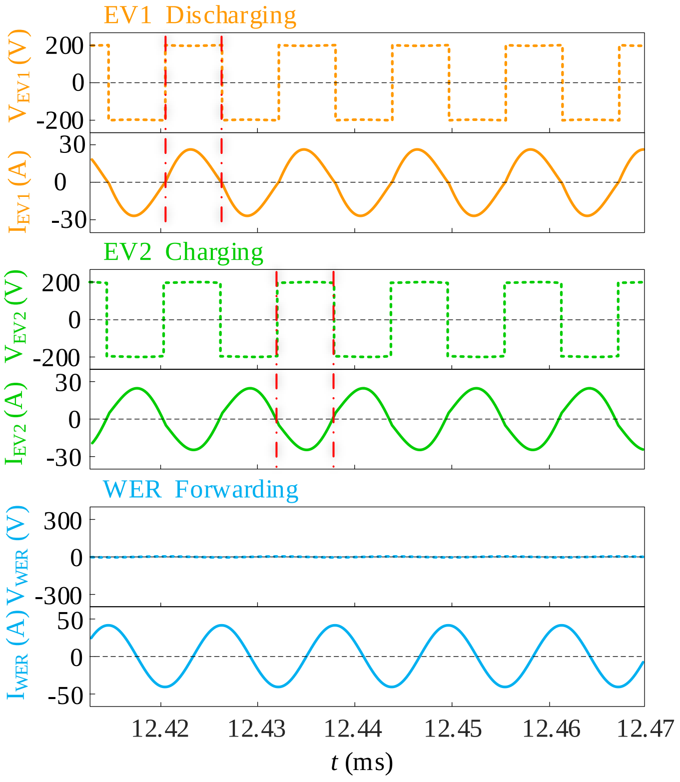
(d)



(e) (f)

Figure 4: Electromagnetic characteristics of three typical energy management scenarios. (a)–(b) Charging-discharging energy balance. (c)–(d) Charging demand excess. (e)–(f) Discharging demand excess. (a), (c) and (e) indicate the electromagnetic field distributions. (b), (d) and (f) indicate the 3-D flux density along the intermediate plane between EVs and WER.

The system performance of the proposed bidirectional wireless charging for wireless energy networks is simulated and demonstrated in three different scenarios, as shown in Fig. 5, in which the hybrid energy storage is represented by pure resistances. Fig. 5(a) shows that WER operates in the energy forwarding mode. In this scenario, the energy supply and demand between two EVs are equal, and the electric energy is transmitted bidirectionally between (dis)charging EVs without energy exchange with WER. In Fig. 5(b), when both EVs demand energy, the WER supplies wireless energy packets to two charging EVs and thus operates in the discharging mode. Fig. 5(c) shows that two discharging EVs simultaneously upload energy packets to the WER when they have extra energy for trading. In this scenario, the WER operates in the charging mode. Therefore, the proposed bidirectional wireless charging over WERs for wireless EV energy networks can achieve rational transmission and distribution of energy assets.



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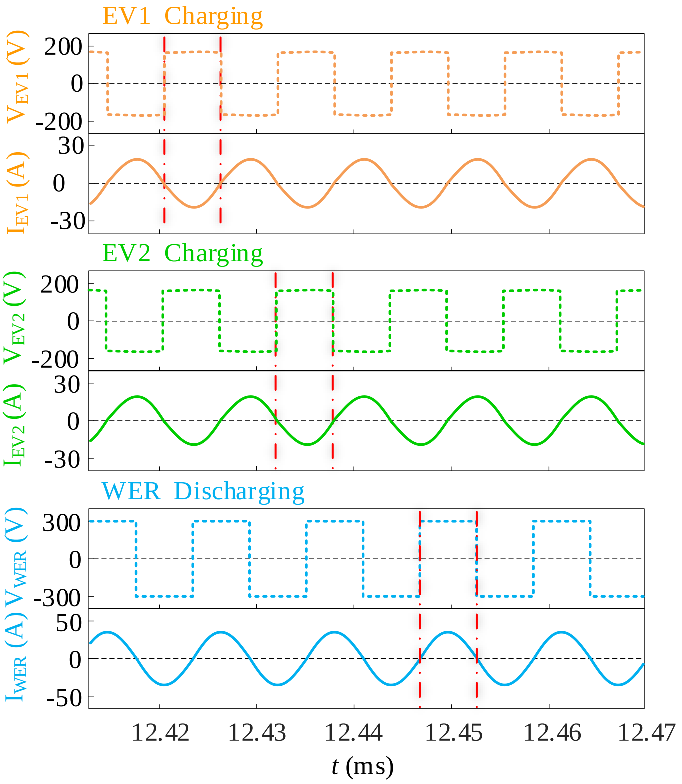

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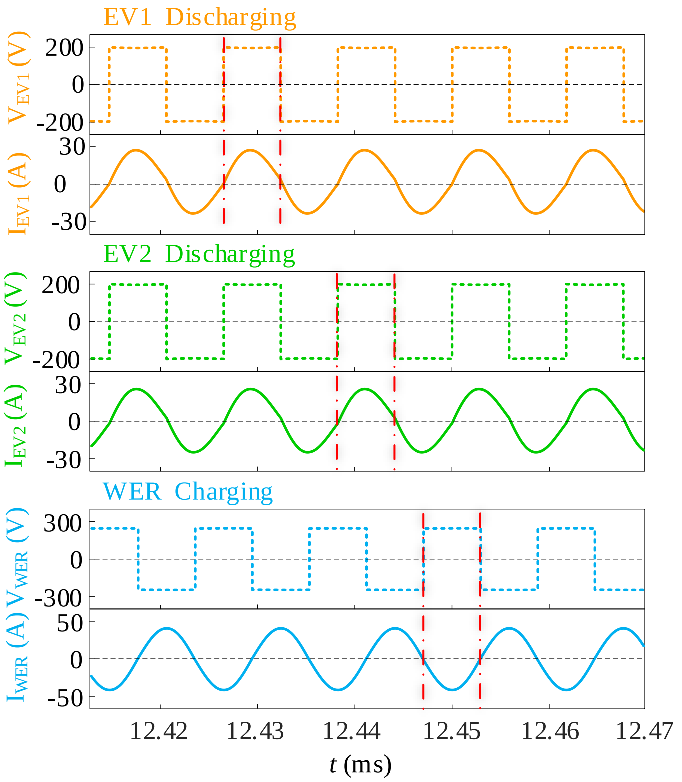
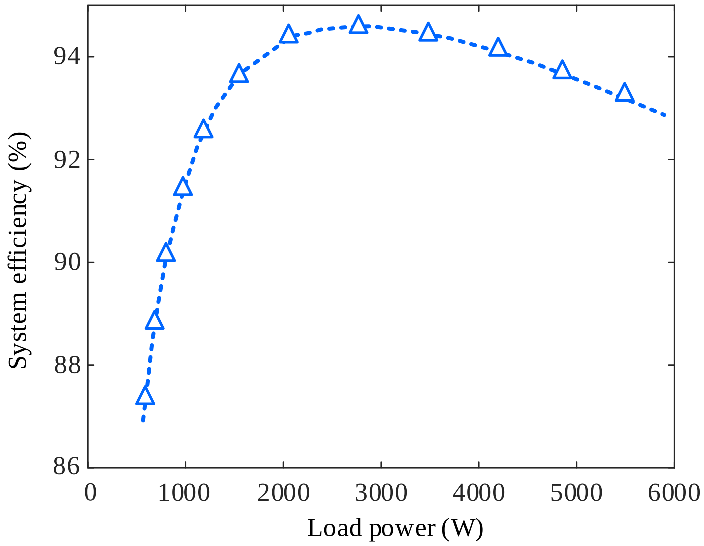


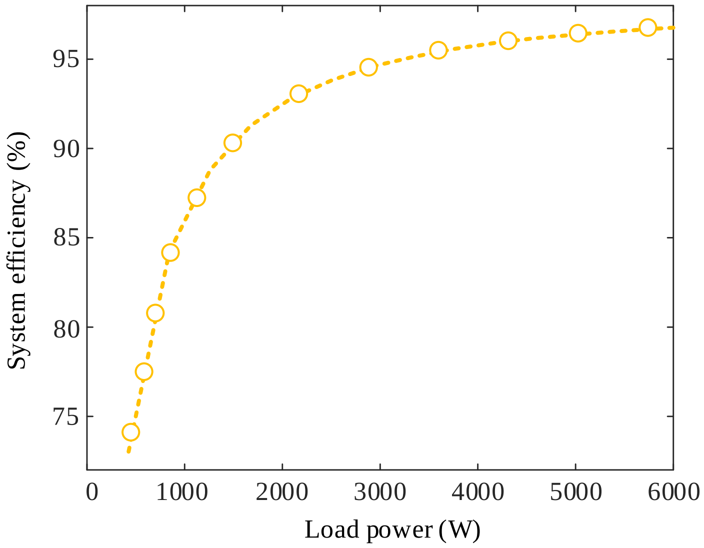
(c)

Figure 5: Simulated results of the proposed bidirectional wireless charging over WERs in the wireless EV energy network. (a) One EV charging and another discharging (WER forwarding). (b) Two EV charging (WER discharging). (c) Two EV discharging (WER charging).

Fig. 6 shows the system efficiency of the proposed bidirectional wireless charging EV energy network under different working scenarios. The system efficiency in the case of one EV charging and another discharging is shown in Fig. 6(a), where a high transmission efficiency can be achieved when the transmission power is over 1000W. In addition, the system efficiencies in the scenarios of two EV charging and two EV discharging are shown in Fig. 6(b) and Fig. 6(c), respectively. The system can maintain high-efficiency operation in a wide range of load power, and with the increase of load power, the system transmission efficiency can be further improved in these two working scenarios. Therefore, the optimal energy flow management scheme can be determined based on the trend of system efficiency in the three scenarios.



(a)



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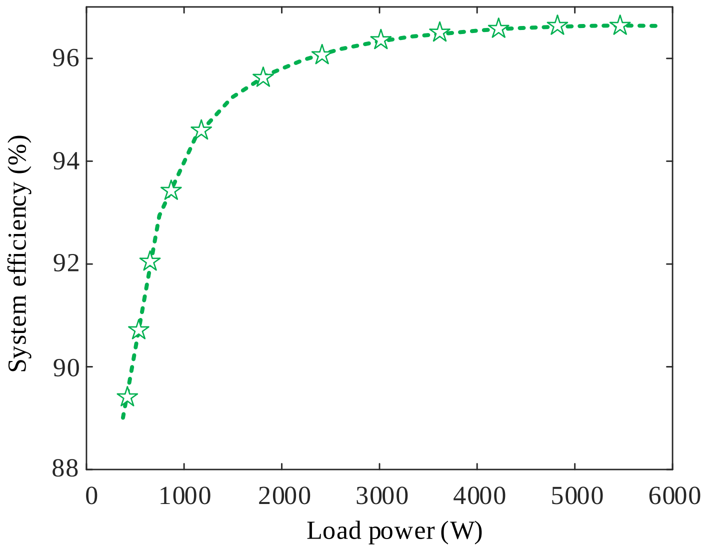

(c)

Figure 6: Simulated results of system efficiencies versus load power. (a) One EV charging and another discharging (WER forwarding). (b) Two EV charging (WER discharging). (c) Two EV discharging (WER charging).

4 Conclusions

In this paper, a bidirectional wireless charging system over WERs is proposed in a wireless EV energy network. The proposed bidirectional wireless charging over WERs can effectively address the range anxiety of EVs and allow for energy transmission and systematic integration with other energy networks into the unified Energy Internet. As mobile energy storage systems, EVs not only realize bidirectional wireless energy transmission but efficiently transmit other energy sources within the Energy Internet, such as renewable energy and natural gas. This helps to promote the network-based sharing and trading of regional energy resources and accelerate the development of intelligent Energy Internet. Theoretical analysis and relevant verification are given to verify the feasibility of proposed bidirectional wireless charging over WERs in wireless EV energy networks.

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