A Review of Wireless Power Transfer Electric Vehicles in Vehicle-to-Grid Systems

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Abstract. Wireless power transfer (WPT) for electric vehicles (EVs) provides further ancillary services for Vehicle-to-grid (V2G) system. This paper reviews the current WPT technologies including their principles and applications in EVs for V2G. The current state-of-the-art of WPT techniques, key technical issues and challenges of WPT in V2G system are comprehensively reviewed, and the research challenges and future trends of WPT in V2G systems are identified and discussed.

Keywords: Wireless power transfer · Electric vehicles · Vehicle-to-grid · Inductive coupler

1 Introduction

Smart grid is expected to be the next generation power grid which combines the stand alone microgrids and large-scale electric power plants. By utilising microsources, such as renewable energy sources, smart grid can control and optimise electricity demands in a more economic and reliable way. However, the integration of power generation mixes brings the uncertainty to the grid planning, operation and control [1]. In the meantime, the adoption of Electric Vehicle (EV) is expected to increase tremendously in the coming years. This will inevitably add substantial loads to the smart grid. As a consequence, identifying and designing strategies toward EVs integration are crucial to preserve the stability and resilience of grid system.

The growing EV market has stimulated the demand for more efficient and convenient way to recharge the battery. One of the main limitations of EV development is the wired charging pattern which to make the users stop their routine and wait for EV charging [2]. The inconveniences and insecure traditional charging mechanisms between vehicle and charging device have led to the establishment of wireless power transfer (WPT) techniques. By introducing WPT in EVs, the obstacles of charging time, range and cost are can be mitigated.

By wirelessly transferring energy to the EV, the charging becomes an easier task. For example, for a stationary WPT system, the drivers just need to park and leave the car. For a dynamic WPT system, the EV can be charged while driving [3]. When an EV connects to the grid, it has little effect on the energy grid planning and operation. However as the number of EVs increases, it is predicted that up to 60% of electricity

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consumption will be consumed by EVs in 2050 [4]. This is a huge and randomized loads to the energy grid. Energy management for the large EVs group is essential for the energy grid in ensuring the balances of supply and demand. Hence, more companies and corporations are increasingly putting their efforts on the EV studies. For instance, the batteries improvement and charging stations [5] with the intention of making EVs towards more prevalent in the near future. Additionally, considering the energy grid distribution that will become essential to the EV system. When EV is connected to the smart grid, it can be operated as active loads that drains energy from the main grid, and as energy storage devices that allows electric energy to be discharged from EV batteries. Thus, the concept of vehicle-to-grid (V2G) is introduced that acts as the provision of energy and ancillary service from an EV to the electric grid [19]. V2G-featured EVs can provide peak shaving, frequency regulation, spinning and non-spinning reserves by optimizing V2G energy scheduling and coordination [6]. These services have been backed up by efforts for standardization of vehicular networking, communication protocols and governmental policies that aim to provide solutions to grid design.

However, the capabilities of WPT EV address not only the attractive potential benefits but also with challenges and possible solutions. For example, the utilisation of adequate WPT technology can enhance the V2G transmission and communication system, and support the EV batteries to be intensively charged/discharged. Among various technical challenges to be overcome such as high mobility of vehicles and multitude of system and application related requirements need to be considered [9]. Such challenges served as the background for studying WPT V2G issues as well as opportunities to increase the grid efficiency. In particular, some of the services, such as energy management model and frequency regulation, are identified to be the most valuable service that EVs can offer in the electricity market [12]. While the aforementioned literatures laid a solid foundation in EV and V2G but limited work has been done in the WPT EV in V2G. In this paper reviews the current WPT technologies, particularly focusing on their principles and applications in relation to EVs for V2G, and identifies the research challenges and future trends of WPT in V2G systems

The remainder of this paper is as follow. In Sect. 2, it presents the fundamentals of WPT techniques for EVs and further addresses different types of charging pattern. In Sect. 3, the V2G system is introduced for the deployment of EV groups and then further investigates the ancillary services and operation challenges. Then, the applications supported by WPT and V2G are discussed in Sect. 4 where technical challenges and trends are addressed. Section 5 concludes and identifies future research problems.

2 Wireless Power Transfer for EV

Figure 1 depicts a typical wireless EV charging system. The basic principle behind the charging system is to utilise the RLC resonators that a high-frequency current in the transmitting coil generates an alternative magnetic field and then transmits to the receiving objects. The efficiency of the energy transaction depends on the number of coils, power electronics convertors and the compensation network [7].

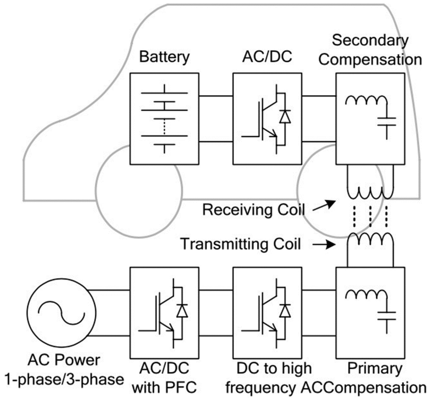

Fig. 1. Typical wireless electric vehicles charging system. Adapted from [2]

There are two main types of WPT technologies, the *near-field* and *far-field* where the energy-carrying medium is the electromagnetic field. The above system utilises the coupled magnetic resonance to transfer power which belongs to the near- field. The far-field technique, on the other hand, uses laser, microwave or radio wave to achieve longer transmission distance. However, the efficiency and controllability are not suitable for EV charging.

By referring to the system as described in Fig. 1 the complex power exchange equation [2] is as follows:

$$\begin{aligned} \dot{S}_{12} &= -\dot{U}_{12}\dot{I}_{12}^{*} = j\omega \dot{I}_1 \dot{I}_2^{*} \\ \dot{S}_{21} &= -\dot{U}_{21}\dot{I}_{1}^{*} = -j\omega M \dot{I}_2 \dot{I}_1^{*}, \end{aligned} \tag{1}$$

Where $\dot{U}_{12}$ and $\dot{U}_{21}$ denote the voltage for primary and secondary coil (compensation) respectively, $\dot{I}_1^*$ and $\dot{I}_2^*$ are the current in two coils, and $\dot{S}_{12}$ and $\dot{S}_{21}$ + are the apparent power between the transmitting and receiving device coils respectively. The level of transmitted power is proportional to the voltage and current in the conductive coils. With a highly reduced resistance, the resonators can transfer energy more efficiently. To obtain an extended operating range as well as sufficiently high transmission efficiency, coupled magnetic is proposed in [8, 23] to enhance the power transfer.

Moreover, a magnetic gear EV charging technology is also available that uses the mechanical force to carry energy based on the interaction between two synchronized permanent magnets as its main coupling mechanism [24]. In WPT area, such technique was first introduced in powering the medical implant with only 6.6 W transfer power at 1.0 cm air gap [10]. By applying this technique with larger power, it can be scaled up to 1.6 kW at 15 cm which is promising for EV charging application [11].

2.1 Technologies of WPT for EV Charging

A. *Stationary charging*

In a stationary charging, the coupler is usually designed in a pad form. However, in EV charging process, the magnetic coupler is separated to meet the larger power transfer gap. From 1997 to 2011, there has been many achievements in applying coupled magnetic resonance for instance, Conductix-Wampfler in New Zealand, HaloIPT and Qualcomm [14]. Using the inductive power transfer technique, the Plusless Power produced by Evantran could transfer an output power of 3.3 kW across 100 mm which is claimed to be 90% efficient compare to the plug-to-battery efficiency [15]. And at the end of 2012, the Plusless announced a trial called Apollo Launch Program that aims to integrate the WPT stationary charging technique to current on-sale EVs across the United State.

B. *Dynamic charging*

The dynamic charging is a way to charge the EV while driving. The major drawback of this technique is the EV's anxiety range that may be the main reason that limits the market penetration of EVs. In the dynamic charging system, the magnetic components are composed of a primary side magnetic coupler and a secondary side pickup coil [16]. The main difference from the stationary charging is that the primary side coupler is placed aside or under the road. With dynamic charging technique, the EV runs freely on the road. However, the system characteristics should be analysed under the coupling variation to support practice.

KAIST [15] demonstrated a great achievement in the project on-line electric vehicles. An OLEV bus system was demonstrated at Expo 2012 that was able to transfer 100 kW through 20 cm air gap with average efficiency of 75% [14]. The potential of WPT in dynamic charging has been identified that wireless charging and discharging can take place without interfering the movements of EVs.

3 V2G System Requirements and Applications

As the ongoing development of WPT EV, the *V2G concept* is introduced which studies the interaction between mass EV charging and the power grid. The basic concept of V2G power is that the EVs can be both charged and discharged in the grid. In V2G system, each vehicle shall be able to: (1) connect to the grid for electrical energy flow, (2) access and transmit the communication signal from the operator, (3) control the vehicle in response to different scenarios. These requirements vary in according to the operation deployment [28]. The bidirectional WPT can provide advanced performance in V2G applications. Figure 2 illustrates the connection between vehicles and the electrical power grid.

An aggregator can be a utility managing EV groups or a third party operating a virtual power plant. It can be viewed as the market coordinator that passes through system

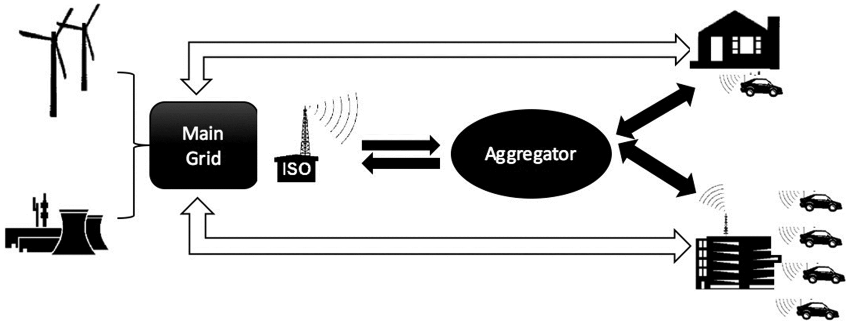

Fig. 2. Smart grid power system with ISO, Aggregator, signal transmission between vehicles, the electric power grid

signals and manages system capacity required to enter the electricity market [27]. Moreover, it is the place that bids with the market participants to provide the most valuable services [6].

The grid operator such as Independent System operator (ISO) broadcasts control signal via cell phone network, direct Internet connection, or power line carrier [28]. The ISO is capable of issuing automatic generation control (AGC) signal to address the ancillary services from EVs. The aggregator manages both the EV fleets and the wholesale market of ISO. In United States, the ISO purchases the regulation capacity service to help aggregators in reducing the financial risk and price volatility [21].

From Fig. 2, the electricity flows from power generators through the grid to electricity users and flows back from EVs to the grid. The ISO sends control signals to the aggregator, and the aggregator develops dispatch algorithms in order to respond the ISO requests. The signal may control the single or multiple EV fleets depending on the request type and dispatch strategy. The batteries in the EVs act as an energy bank which can be connected to the grid more easily, and the bidirectional function of WPT can be realized using the active switch between the rectifiers [30]. Furthermore, studies show that by introducing the WPT technology in V2G design, the drivers are more willing to connect their EVs into the grid [31], which can then maximise the V2G benefits.

3.1 V2G Related Applications and Challenges

V2G system features in transforming EVs from potentially problematic loads into distributed energy sources that generate values for both the utility and EV owners. The electricity sources shall be controlled in real-time by the ISO to ensure the efficiency of power transfer. Some services such as frequency regulation, spinning reserve and load hiding are discussed in this section, along with the challenges associated with the services.

The *frequency regulation* techniques in [6, 21, 26] used to tune the frequency and voltage of the grid by matching generation to load demand. By using the fast-ramping feature of EVs, the regulation can be controlled under the direct real-time control. However, determining the regulation capacity can be difficult in the process as the EV's user behaviour is randomized. Hence, an intelligent dispatch algorithm is required. In [6, 19, 21], the dispatch algorithms were proposed according to the price-based/event-based, incremental/binary or unidirectional/bidirectional charging rate scenarios.

Spinning reserve refers to the additional generating capacity that remains in standby mode to provide power upon request. Spinning reserves are remunerated by the amount of time they are available and ready [28]. In V2G system, the EVs have high response rate and require short time to provide power. The challenge here is to report the number of EVs that can remain online during the contracted/tendered period. Furthermore, the contract length is limited by the state of charge (SoC) in EV battery. The state-of-art stochastic modelling of EV user behaviour were proposed in [4, 17] to calculate the contract/tender length and duration.

V2G system is also suitable in the application of *load hiding* in household electricity consumption profile. The appliance operation activities can be mapped with household routines, which can further be exploited to infer customer preferences and privacy [22], V2G system utilises EV rechargeable battery as controllable load to mitigate the privacy leakage of the customers. The key concept here is to distort the household consumption profile based on different algorithms, such as the best effort in [18], or stepping approach in [18]. However, the current researches are based on a series of idealisation for driving pattern and household base load. The future work should include the uncertainty of household load, EV arrival time and SoC.

4 WPT Supported V2G Applications

Over the past decades, so many efforts have been accomplished to improve conversion and utilisation of energy to reduce the dependency in fossil fuel. However, the fact is that tremendous amount of renewable generations are only able to realise a small portion of utilizable loads. For example, less than 1/3 of wind farms are connected to the grid in China due to the intermittent power dispatch and transmission network limitations [3]. An automatic and bidirectional charging and discharging system is essential for the best interaction between EVs and renewables, where a fleet of EVs need to be simultaneously powered. Especially, the WPT system adds the flexibility to the V2G system which can mitigate the stochastic nature of user behaviour and intermittency of renewable sources.

Involving renewables for compensating the required demand of EVs is an ideal solution for the V2G operation. Several studies have been conducted on the inductive power transfer system with various topologies [32, 33]. The system model with a dynamic multivariate steady-state mathematical model was presented in [34], which is suitable for V2G applications. The representation of the mutual coupling between the circuits shows the effect of the applied control to manage the power transfer. Hence, the study of energy flow between WPT EVs and V2G enhances the grid stability and improves the power quality for further applications.

The V2G power that the system can provide is limited by many factors, such as the infrastructure line capacity limit and vehicle's stored energy. More specifically, the limit is the energy stored on-board divided by the time drawn. It can be expressed as [28]:

$$P_{\text{vehicle}} = \frac{\left(E_{\text{s}} - \frac{d_{\text{d}} + d_{\text{rb}}}{\eta_{\text{veh}}}\right)\eta_{\text{inv}}}{t_{\text{disp}}}, \tag{3}$$

Where $P_{vehicle}$ is the maximum power from V2G in kW, E_s the stored energy available to the inverter, d_d is the distance driven, d_{rb} is the distance of the range buffer, η_{veh} is the vehicle efficiency, t_{disp} is the time where the vehicle's stored energy is dispatched. It is clear that using WPT to minimize the factor t_{disp}, this will increase the power capacity and thus improves the power efficiency.

Furthermore, EV can be used as the supplementary for power delivery system with the help of WPT technology. A mathematically tractable framework is constructed for transporting energy from remote renewable resources to the loads using the dynamic wireless charging [3]. The wireless charging system can be embedded in the pavement and thus transforms roads into public charging facilities. It provides a pervasive and wireless charging platform for integrating the transportation and power networks. The WPT technique allows energy to be transmitted seamlessly with EVs as energy carriers, which provides a new area of WPT EV utilisation in V2G system. The author [35] analyses the transportation and power networks coupled by EVs that electrify the roads as the charging infrastructures. The electrified roads then become nodes in the power flow, and the prices at different nodes will influence the route choices. The optimal calculation towards charging cost, driving routines and power distribution associated with the coupled networks may become complex. With fast- paced technological advancement, this will increase the robustness feature of EV wireless charging capability.

4.1 Challenges and Future Trend of WPT

In V2G system, market penetration of WPT technique is still critical as there are many challenges to be overcome. It can be summarized as three aspects: (1) *achieving high efficiency*: 90% of overall power transmission efficiency is typically to be considered as efficacious for WPT technique. To achieve this, the coil design is the most important part in the whole system. The dimension of coil will define the upper limit of the power capacity and the efficiency will be affected by the quality factor of coil [15]. (2) *alignment tolerance*: A system shall be fairly tolerant of misalignment between transmitter and receiver in both the stationary and dynamic charging. One of the solutions is to adjust configuration of the ferrite cores to achieve better alignment tolerance [30]. (3) *dynamic charging control*: The consistency between the road side and on-board system shall be designed properly at the same time to ensure the consistency and accommodate various vehicle types.

Moreover, when charging an EV battery wirelessly, there is a high frequency magnetic field existing between the transmitting and receiving coils. The large air gap between the two coils causes a high leakage field where can arise safety concerns of such high frequency magnetic field. However, it is clear that the vehicle electrification is unavoidable in the future. The wireless charging techniques would provide the foundation for mass EV market penetration regardless of battery technology.

In EV wireless charging area, there have been many pre-commercial demonstrations and commercial kits that are readily available in the market. And many works have been done to provide an easier way to implement the smart grid functionalities and maximise the V2G benefits. The foreseeing trend of WPT techniques shall focus on the mass adoption of existing available EVs, for example, magnetic structure design, high efficiency RF amplifier and converter control strategy design [16]. International standards and safety regulations must be implemented to ensure the shielding capacity for protecting users. Besides, it is even more important to exchange larger amount of information between the grid and vehicle side wirelessly in the WPT system. The communication design shall be efficient for real- time, large-volume and accurate signal response.

5 Conclusion

This paper presented a review of WPT technology in EVs and the integration of WPT in V2G system. It is clear that introducing inductive WPT into the EV market will accelerate the penetration of transport electrification. Furthermore, the integration of WPT can alter the distribution and operation of V2G system which will inevitably increase the potential of enhancing the power delivery efficiency. Future studies in network communication, WPT technology and V2G topology design are essentially needed in the present, upcoming and future terms.

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References

1. Liang, H., Zhuang, W.: Stochastic modeling and optimization in a microgrid: a survey. Energies **7**(4), 2027–2050 (2014)
2. Li, S., Mi, C.C.: Wireless power transfer for electric vehicle applications. IEEE J. Emerg. Sel. Top. Power Electron. **3**(1), 4–17 (2015)
3. Lam, A.Y.S., Leung, K.C., Li, V.O.K.: An electric-vehicle-based supplementary power delivery system. In: 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, pp. 307–312 (2015)
4. Kriukov, A., Gavrilas, M.: Smart energy management in distribution networks with increasing number of electric vehicles. In: 2014 International Conference and Exposition on Electrical and Power Engineering (EPE), Iasi, pp. 1039–1044 (2014)
5. Lam, A.Y.S., Leung, Y.W., Chu, X.: Electric vehicle charging station placement: formulation, complexity, and solutions. IEEE Trans. Smart Grid **5**(6), 2846–2856 (2014)
6. Yao, E., Wong, V.W.S., Schober, R.: Robust frequency regulation capacity scheduling algorithm for electric vehicles. IEEE Trans. Smart Grid **PP(**99), 1–14
7. Kavitha, M., Bobba, P.B., Prasad, D.: Investigations and experimental study on Magnetic Resonant coupling based Wireless Power Transfer system for neighborhood EV's. In: 2016 IEEE 6th International Conference on Power Systems (ICPS), New Delhi, pp. 1–6 (2016)

8. Kim, J., et al.: Coil design and shielding methods for a magnetic resonant wireless power transfer system. Proc. IEEE **101**(6), 1332–1342 (2013)
9. Karagiannis, G., et al.: Vehicular networking: a survey and tutorial on requirements, architectures, challenges, standards and solutions. IEEE Commun. Surv. Tutorials **13**(4), 584–616 (2011). Fourth Quarter
10. Suzuki, S., Ishihara, M., Kobayashi, Y.: The improvement of the noninvasive power-supply system using magnetic coupling for medical implants. IEEE Trans. Magn. **47**(10), 2811–2814 (2011)
11. Li, W.: High efficiency wireless power transmission at low frequency using permanent magnet coupling (Doctoral dissertation, University of British Columbia) (2009)
12. Huang, S., Wu, L., Infield, D., Zhang, T.: Using electric vehicle fleet as responsive demand for power system frequency support. In: 2013 IEEE Vehicle Power and Propulsion Conference (VPPC), Beijing, pp. 1–5 (2013)
13. Nguyen, H., Khodaei, A., Han, Z.: A Big Data scale algorithm for optimal scheduling of integrated microgrids. IEEE Trans. Smart Grid **PP**(99), 1 (2015)
14. Cirimele, V., Freschi, F., Mitolo, M.: Inductive power transfer for automotive applications: State-of-the-art and future trends. In: 2016 IEEE Industry Applications Society Annual Meeting, Portland, OR, USA, pp. 1–8 (2016)
15. Qiu, C., Chau, K.T., Liu, C., Chan, C.C.: Overview of wireless power transfer for electric vehicle charging. In: Electric Vehicle Symposium and Exhibition (EVS27), 2013 World, Barcelona, pp. 1–9 (2013)
16. Suh, I.S., Kim, J.: Electric vehicle on-road dynamic charging system with wireless power transfer technology. In: 2013 IEEE International Electric Machines & Drives Conference (IEMDC), Chicago, IL, pp. 234–240 (2013)
17. Callaway, D.S., Hiskens, I.A.: Achieving controllability of electric loads. Proc. IEEE **99**(1), 184–199 (2011)
18. Yang, L., Chen, X., Zhang, J., Poor, H.V.: Optimal privacy-preserving energy management for smart meters. In: IEEE INFOCOM 2014 - IEEE Conference on Computer Communications, Toronto, ON, pp. 513–521 (2014)
19. Sortomme, E., Cheung, K.W.: Intelligent dispatch of Electric Vehicles performing vehicle-to-grid regulation. In: 2012 IEEE International Electric Vehicle Conference (IEVC), Greenville, SC, pp. 1–6 (2012)
20. Liu, Q., Golinński, M., Pawełczak, P., Warnier, M.: Green wireless power transfer networks. IEEE J. Sel. Areas Commun. **34**(5), 1740–1756 (2016)
21. Yao, E., Wong, V.W.S., Schober, R.: Risk-averse forward contract for electric vehicle frequency regulation service. In: 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, pp. 750–755 (2015)
22. Sun, Y., Lampe, L., Wong, V.W.S.: Combining electric vehicle and rechargeable battery for household load hiding. In: 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, pp. 611–616 (2015)
23. Wang, C.-S., Stielau, O.H., Covic, G.A.: Design considerations for a contactless electric vehicle battery charger. IEEE Trans. Industr. Electron. **52**(5), 1308–1314 (2005)
24. Jian, L., Chau, K.T., Jiang, J.Z.: A magnetic-geared outer-rotor permanent-magnet brushless machine for wind power generation. IEEE Trans. Ind. Appl. **45**(3), 954–962 (2009)
25. Etezadi-Amoli, M., Choma, K., Stefani, J.: Rapid-charge electric-vehicle stations. IEEE Trans. Power Delivery **25**(3), 1883–1887 (2010)
26. Ha, D.L., Guillou, H., Martin, N., Cung, V.D., Jacomino, M.: Optimal scheduling for coordination renewable energy and electric vehicles consumption. In: 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, pp. 319–324 (2015)

27. Han, S., Han, S., Sezaki, K.: Development of an optimal vehicle-to-grid aggregator for frequency regulation. IEEE Trans. Smart Grid **1**(1), 65–72 (2010)
28. Kempton, W., Tomić, J.: Vehicle-to-grid power fundamentals: calculating capacity and net revenue. J. Power Sources **144**(1), 268–279 (2005)
29. Li, H., Dán, G., Nahrstedt, K.: Lynx: authenticated anonymous real-time reporting of electric vehicle information. In: 2015 IEEE International Conference on Smart Grid Communications (SmartGridComm), Miami, FL, pp. 599–604 (2015)
30. Lee, S., Huh, J., Park, C., Choi, N.S., Cho, G.H., Rim, C.T.: On-Line Electric Vehicle using inductive power transfer system. In: 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, pp. 1598–1601 (2010)
31. Huang, X., Qiang, H., Huang, Z., Sun, Y., Li, J.: The interaction research of smart grid and EV based wireless charging. In: 2013 IEEE Vehicle Power and Propulsion Conference (VPPC), Beijing, pp. 1–5 (2013)
32. Kabalo, M., Berthold, F., Blunier, B., Bouquain, D., Williamson, S., Miraoui, A.: Efficiency comparison of wire and wireless battery charging: based on connection probability analysis. In: 2014 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, pp. 1–6 (2014)
33. Ayano, H., Yamamoto, K., Hino, N., Yamato, I.: Highly efficient contactless electrical energy transmission system. In: IEEE 2002 28th Annual Conference of the IECON 2002 Industrial Electronics Society, vol. 2, pp. 1364–1369 (2002)
34. Mohamed, A.A.S., Berzoy, A., Mohammed, O.: Power flow modeling of wireless power transfer for EVs charging and discharging in V2G applications. In: 2015 IEEE Vehicle Power and Propulsion Conference (VPPC), Montreal, QC, pp. 1–6 (2015)
35. He, F., Yin, H., Zhou, J.: Integrated pricing of roads and electricity enabled by wireless power transfer. Transp. Res. Part C Emerg. Technol. **34,** pp. 1–15 (2013). ISSN 0968-090X