RECTIFIER LOAD ANALYSIS FOR ELECTRIC VEHICLE WIRELESS CHARGING SYSTEM USING SYNCHRONOUS REFERENCE FRAME WITH SPACE VECTOR PULSE WIDTH MODULATION

Mr. Satish Kumar[1], Ms. A. Thakur[2]
[1]M.Tech Research Scholar, [2]Associate Professor
Department of Electrical Engineering
Shree Satya Sai University of Technology and Medical
Sehore(Madhya Pradesh),India

Abstract - In the recent developments of simulation speed and power electronics, the field of wireless power transfer has been developed significantly. In the future transport area, electric vehicles are considered as replacement of oil powered internal combustion engine driven vehicles. Electric Vehicles (EV) have been proposed to achieve environmental friendly transportation. Even though the EV usage is currently increasing, a technology breakthrough would be required to overcome battery related drawbacks. To address battery related limitations, the concept of Wireless Power Transfer (WPT) enabled EVs have been proposed in which EV is being charged while it is in motion or stationary.

In this paper, the technologies for electric vehicle wireless charging are reviewed using the method of inductive coupling. WPT is the transfer of electrical power from the power source to a load without the use of physical connectors. WPT circuitry is placed inside the vehicle which gets activated when the vehicle reaches the charging area. The primary coil is supplied from the charging station. Flux is radiated out of the primary coil and gets induced with secondary coil present in the EV. The induced voltage from secondary coil is then regulated, rectified and used to charge the EV battery. In this paper a miniature model of Electric Vehicle is charged in an effective way without using cables and other plug-in technology. Efficient wireless power transmission is done and control over electromagnetic induction and effective charging of battery will be achieved

Index Terms - EV, SAPF, WPT.

.

I. INTRODUCTION

The EVs engineering is merged with the automotive and electrical engineering by including a motor, a power electronic converter, a controller, a battery and an energy management system. Each module have to be able to work together and have the best performance to achieve the required driveability at the maximum energy efficiency. In applications of EV wireless charging, rectifier and output filter capacitor are needed to convert the high frequency AC to DC, in order to charge the power battery. Rectifier and the circuit after it are usually equivalent to a pure resistance load to design the system or control strategy [1]. The stray parameters and non-ideal behaviours of the devices will become obvious at the high frequency range [2]. Also, rectifier input impedance can be affected by the input inductance and other parameters. So, it will bring some deviations, if only considering WCS rectifier input impedance as a pure resistance. Actually, rectifier input impedance of EV wireless charging system contains both resistance part and inductance part [X78]. For dedicated drive applications, it would be very helpful to have a simulator that extends high-level system simulation down to the device level. At the device level, it is possible to model motor losses, pulse-width modulated (PWM) inverter action, and the fast dynamics needed to implement torque controls and nonlinear loops.The non-linear process of rectifier load will bring some difficulties to system compensation network design. So, actual equivalent input impedance of WCS rectifier load should be considered, while designing the compensation networks. Load estimation of WCS has faced the same problem. Effects of the rectifier load could complicate the equations used for load estimation [6], and lead to the increasing of calculation and control complexity. Hence, a pure resistance load is approximately used for most of the load estimation, detection, or optimal load tracking [8]. In literature method to quantitatively analyse the equivalent load of WCS rectifier is put forward in the paper firstly. The equivalent load can be independently calculated through the parameters of the rectifier circuit, and the results are basically not affected by other WCS parts. Secondly, a compensation network design method is proposed considering the equivalent impedance of the rectifier load, especially the equivalent inductance. Thirdly, the effects of the rectifier non-linear process are taken into count to estimate the system load resistance. The proposed primary side load estimation method only adopts high frequency voltages, doesn’t need to measure the currents, and can avoid the phase delay deviations. It does not require wireless communication between the primary and secondary sides. In this paper review of all parameters affecting on performance of EV.

2. LITERATURE REVIEW

Wireless electric vehicle charging techniques have been popular for some time now due to their safety, convenience and efficiency. There are several ways to increase the WPT efficiency of a system. First is by the proposed Series–Series (SS) resonant compensation topology alongside the design of radio frequency feedback (Tan, 2017). Yanjie Guo, Lifang Wang,2018 et al This paper delivers a brief history throw lights on wireless charging methods, highlighting the pros and cons. Then, the paper aids a comparative review of different type's inductive pads, rails, and compensations technologies done so far. The role and importance of power electronics and converter types used in various applications are discussed. The batteries and their management systems as well as various problems involved in WPT are also addressed. Different trades like cyber security economic effects, health and safety, foreign object detection, and the effect and impact on the distribution grid are explored.

Naoui Mohamed, Flah Aymen 2022 et al. In the proposed system, receiver coils have been added to maximize charging power by offering a dynamic mathematical model that can describe and measure source-to-vehicle power transmission even though it is in motion. In the proposed mathematical model, all physical parameters describing the model were presented and discussed. The results showed the effectiveness of the proposed model. Also, the experimental tests confirmed the validity of the simulation results obtained by providing two coil receivers under the vehicle. Aganti mahesh, bharatiraja et al. paper delivers a brief history throw lights on wireless charging methods, highlighting the pros and cons. Then, the paper aids a comparative review of different type's inductive pads, rails, and compensations technologies done so far. The static and dynamic charging techniques and their characteristics are also illustrated. The role and importance of power electronics and converter types used in various applications are discussed. The batteries and their management systems as well as various problems involved in WPT are also addressed. Different trades like cyber security economic effects, health and safety, foreign object detection, and the effect and impact on the distribution grid are explored. The other technique employed was by finding a reference voltage in the secondary side using the simultaneous estimation of the secondary side's mutual inductance and a voltage at the primary side (Hata, 2016). In addition, the compensation topologies play a key role in the power transfer efficiency, therefore, this paper gives a detailed comparison between the SS and PS compensation topologies (Ravikiran, 2017). Simulation results show that the PS topology is good for power applications of medium range. This paper uses secondary side LCC impedance matching circuit under a rectifier load to enhance the maximum efficiency transferred (Liao, 2017).

To keep up with the pace of battery capacities, it is essential to increase the rate at which an electric vehicle battery is wirelessly charged. One of the ways of increasing battery performance is by designing the coupling factor of the coil system appropriately and ensuring that the rate of displacement is large (Klaus, 2017). Another way to increase the power transfer system of an electric vehicle is to use two extra coils in between the transmitter and the receiver coils with experimental verification with a 6.6KW circuit (Tran, 2018). These results in an efficiency of 97.08% for 3.4KW.For different challenges associated with WPT to be addressed, this paper proposed employing an20improved floor surface for shielding the transmitting coil area, high-frequency switches with large band gap switches and polygon iron core (Mahmud, 2017). These components help to improve the system's efficiency. Subsequently, a wireless power charging system requires a constant current flow and output voltage alongside a maximum efficiency. This leads to the design of a control based maximum efficiency tracking system that controls the transmitter current based on the information the receiver receives via Bluetooth (Yeo, 2017).

This gives a constant output voltage and constant current flow with increased efficiency in the WPT system. A fixed voltage source and fixed current load are modelled, analysed and verified experimentally to increase the wireless power charging system's efficiency (Zhang, 2017). The voltage transmitted in a wireless power transfer depends on the distance between two coils. This paper implements a proportional integral controller at the receiver side of the wireless power transfer to eliminate the variation of voltage for a varied distance between the two coils (Yeo, 2017).Furthermore, the high electromagnetic field generated between the transmitter coil and the receiver coil is detrimental to human life, hence the need to alleviate the magnetic field leakage between the coils. This high electromagnetic field leakage between the two coils is because of the large air gaps that occur between the transmitter coil and the receiver coil (Kim, 2016; Haque, 2018).

One of the ways to lower the magnetic field leakage between the two coils is by designing a system that generates low magnetic leakage of about 19.8mG and high WPT efficiency of 96% over a156mm air gap (Zhang, 2016). To lessen system loss, the transmitting coil was designed in a way to turn on or off while the EV is in motion (Cho, 2016) with an optimal receiving coil design ratio of radius 4, height 5 and distance 13 resulting to a 50% higher power transfer efficiency. The work of Cho investigated the relation between the coupling coefficient and the efficiency of Grouped Periodic Series Spiral Coupler (GPSSC) (Cho, 2016). Another way to reduce the electromagnetic field leakage between the transmitter and the receiver and at the same time increase the power transfer21efficiency is to use meta materials, which help to concentrate the magnetic field (Dolara, 2017).

A meta material was designed in this paper which showed that efficiency was increased to about44.2% and magnetic leakage decreased to about 3.49dBm over 20 cm distance. Also, for the risk associated with exposure to an electromagnetic field of the power pad of an electric vehicle to be decreased, a magnetic shielding technique was introduced using conductive panels (Campi, 2017), and an aluminium plate and aluminium ring (Campi, 2017). Here in this work there were considerations for the conducted emission in charging the electric vehicle wirelessly using the SS and LCC compensation topologies (Cho, 2016). Results show that SS topology reduces the conducted emissions of WPT (Cui, 2018).

This paper presented a control strategy for PWM converter in electric vehicle, with a variable structure current controller as the inner-loop and a fuzzy adaptive PI voltage controller as the outer-loop. A fuzzy adaptive PI voltage controller with the direct voltage error and the slope of the error was designed (Lili Qu1,2 , Bo Zhang 2008).

S. A. Akintade*, Y. Jibril et al Shunt Active Power Filter (SAPF) for harmonic reduction. The current harmonics are being caused by nonlinear characteristic of power electronics based equipment's which increase power losses and in turn reduce power quality. Synchronous Reference Frame (SRF) was used as a control strategy and for reference harmonic current generation and Space Vector Pulse Width Modulation (SVPWM) was adopted as switching signal generation.

3. ELECTRIC VEHICLES AND COMPOSITION OF THE WIRELESS CHARGING SYSTEM

EVs have drawn the attention of governments and companies as a result of growing concerns about environmental issues and the economic benefits of renewable energy. Electric vehicles (EVs) are widely recognised as one of the most effective options for reducing oil dependency and greenhouse gas emissions.

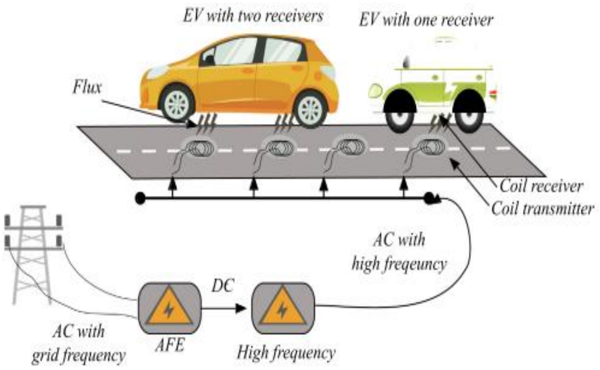


Figure 1: Wireless transmitter system composition

Individual components or systems in EVs, such as electric machines, driving systems, batteries, fuel cells, on-board renewable energy, and so on, have been the focus of EV innovations in recent years. EVs, on the other hand, are playing a new role as energy exchange with the power grid, thanks to the emerging concept of the smart-grid, or micro-grid, because they are capable of not only drawing energy from the power grid, but also delivering energy back to the grid via a bidirectional charger [2].The transmitter part is installed on the road and coupled to a series of electronic equipment that guarantees the adaptability between the receivers and the AC power source, as illustrated in Fig. 1. It presents the initial energy AC power connected to the active front end (AFE) converter that provides a controllable DC voltage. This part of the transmitter block is amended by a power factor corrector (PFC) block, which supervises the reactive power flowing from the source to the transmitter, to ensure grid stability. A high-frequency (HF) full-bridge inverter is then used to deliver a high excitation current to the transmitter coil.

4. STRUCTURE OF MODEL

Full-bridge diode rectifier is the most commonly used topology in EV wireless charging system. Also, dual-side *LCC* compensation networks can provide several appropriate design degrees of freedom to achieve several system performance indicators at the same time. Moreover, it can be designed to make the system resonant frequency independent of the load condition. So we discuss the rectifier load on the basis of this kind of topology.

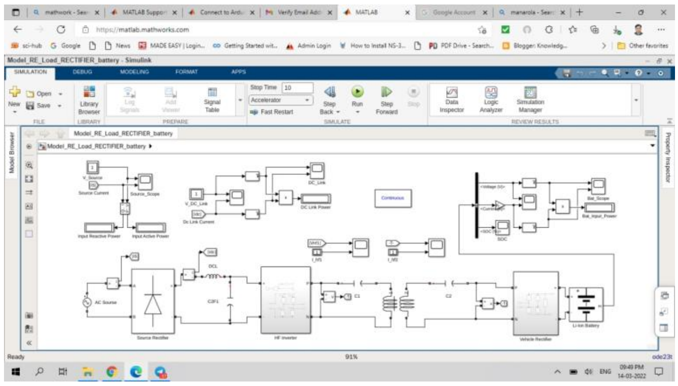


Fig. 2 Simulation model

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \mathbf{A}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \mathbf{B}\begin{bmatrix} u_s \\ u_{dio} \end{bmatrix}, \quad y = \mathbf{C}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}. \tag{1a}$$

Where, impedance matrixes **A**, **B**, and **C** are given by (1b).

$$\mathbf{A} = \begin{bmatrix} -\frac{1}{L_s}(R_{Ls} + 2R_{dio} + \frac{R_L R_{Co}}{R_L + R_{Co}}) & -\frac{1}{L_s}(1 - \frac{R_{Co}}{R_L + R_{Co}}) \\ \frac{R_L}{C_o(R_L + R_{Co})} & -\frac{1}{C_o(R_L + R_{Co})} \end{bmatrix}, \tag{1b}$$

$$\mathbf{B} = \begin{bmatrix} 1/L_s & -2/L_s \\ 0 & 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} \frac{R_L R_{Co}}{R_L + R_{Co}} & 1 - \frac{R_{Co}}{R_L + R_{Co}} \end{bmatrix}.$$

Then, the input variables and the initial values of the state variables are given by (2), according to the schematic waveforms in Fig.2; where, ω is system angle frequency; the diode forward voltage drop is treated as a constant value *Vdio*. Since only a few fluctuations exist on the voltage of *Co* and the voltage drop on *RCo* is very small, their influences can be ignored, and the initial value of *x2* can be approximately equivalent to a DC voltage variable *Vd*. Also, amplitude of *us* is defined as *Vs*, and it will be affected by WCS parameters, such as source voltage, mutual-inductance, etc. But the amplitudes of *urec* and *irec* are proportional to *Vs*. So, *Vs* can be treated as a known variable.

$$u_{s+} = V_s \sin(\omega t + \theta_b), \quad u_{dio} = V_{dio}, \quad \mathbf{x}_+(0) = [0, V_d]^T. \tag{2}$$

Then, the input variables and the initial values of the state variables are given by (2), according to the schematic waveforms in Fig.2; where, ω is system angle frequency; the diode forward voltage drop is treated as a constant value *Vdio*. Since only a few fluctuations exist on the voltage of *Co* and the voltage drop on *RCo* is very small, their influences can be ignored, and the initial value of *x2* can be approximately equivalent to a DC voltage variable *Vd*. Also, amplitude of *us* is as source voltage, mutual-inductance, etc.

But the amplitudes of *urec* and *irec* are proportional to *Vs*. So, *Vs* can be treated as a known variable.

$$i_{rec} = \frac{1}{\omega L_s} \int_{\theta_b}^{\theta} (V_s \sin\theta - V_d) d\theta. \quad (3)$$

Furthermore, *Vd* and *θb* should be calculated to solve the state space equation. On the WCS normal working conditions, the value of *Vdio* and the voltage drops on *Rdio* and *RLs* are much smaller than the ones of *Vs* and *Vd*. So, the voltage on *Ls* is approximately equivalent to *Vs* sin*θ* - *Vd*, and the expression of *irec* can be given by (3), according to the relationship between the voltage on an inductor and the current flowing through it.

$$V_d = (2V_s \cos\theta_b) / \pi. \quad (4)$$

As shown in Fig.2, *irec*=0, when *θ*=*θf*=*θb*+*π*. So, one relationship between *Vd* and *θb* can be got and given by (4).
As shown in Fig.2, *irec*=0, when *θ*=*θf*=*θb*+*π*. So, one relationship between *Vd* and *θb* can be got and given by (4).

Also, the DC load current *Id* can be calculated by (5), which is the average value of *id* in the positive half cycle.

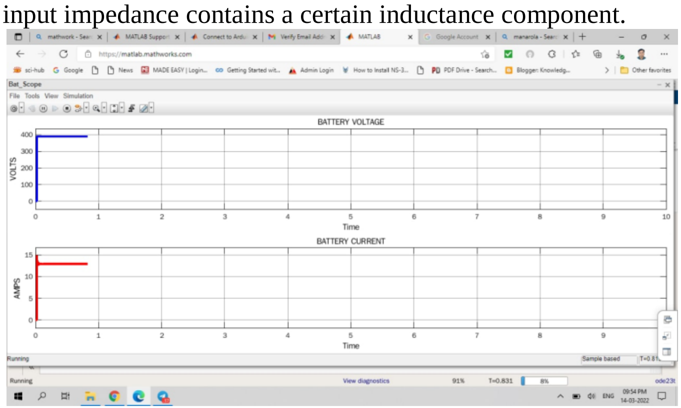
$$I_d = \frac{1}{\pi \omega L_s} \int_{\theta_b}^{\theta_b+\pi} \int_{\theta_b}^{\theta} (V_s \sin\theta - V_d) d\theta \quad (5)$$
$$= (V_s(2\sin\theta_b + \pi\cos\theta_b) - \pi^2 V_d / 2) / \pi\omega L_s.$$

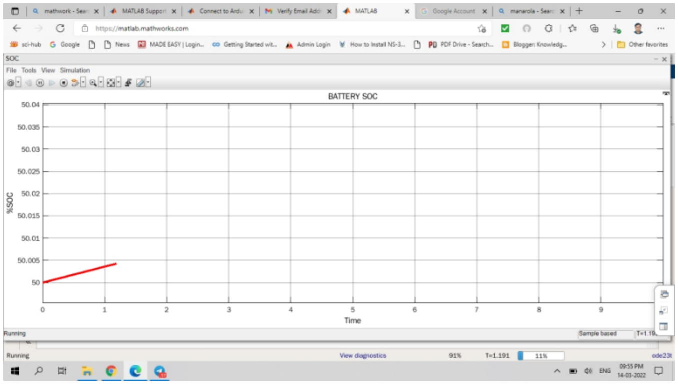
Because *Id* =*Vd* /*RL*, another relationship between *Vd* and *θb* can be got and given by (6).

$$V_d = V_s(2\sin\theta_b + \pi\cos\theta_b) / (\pi(\omega L_s / R_L + \pi/2)). \quad (6)$$

5. SIMULATIONS AND REULTS

An EV wireless charging prototype is developed to verify the rectifier load analysis results and the proposed methods. A full-bridge single-phase inverter with MOSFETs is assigned as the power source. System load is a full-bridge diode rectifier with load resistors. Firstly, experimental waveforms of the rectifier input voltage and current under the condition of standard parameter values. . Moreover, import the experimental data to the software Matlab, and the amplitudes and phase angles of the fundamental waves will be calculated through the FFT (fast Fourier transform) program. So, the fundamental waves can be drawn by Matlab .It suggests that the fundamental wave of rectifier input current lags behind the one of rectifier input voltage, which means the rectifier input impedance contains a certain inductance component.





6. CONCLUSION

In this paper, a modular design for a wireless power transfer system was designed and assessed. The proposed advantage is to offer better tolerance to misalignment, and mitigate the presence of foreign and live objects. The proposed design has shown an improved response to misalignment when analyzed with the analytical models, and compared to a conventional coil of the samearea. The advantage in the area of foreign and live object mitigation is offered as well. The modularity can offer mitigation once such a parasitic object is detected. Another advantage is the ability to cater for a variety of secondary coil geometries by turning on the aligned primary modules with secondaries of various geometries. The analytical models have been verified experimentally, and by Finite Element Modelling. The efficiency of the design remains to be studied, in assessing the cost-to-benefit of the introduced coil material, control connections,and switches.
Finally, the established model, the proposed rectifier load calculation method, compensation network design method, secondary and primary side load estimation methods have been verified, based on the developed EV wireless charging prototype. The experimental results have shown the following conclusions: the equivalent input impedance of rectifier load is mainly affected by system load resistance and rectifier input inductance; rectifier load equivalent inductance will impact system performances, and should be considered for compensation network design; the proposed load estimation methods have good accuracy, but still need to

be improved in further research; the proposed rectifier load calculation method and system load estimation methods all have good robustness, on conditions of WCS parameter variations. Although the works in this paper are conducted based on the specific system, they can be extended to more applications, such as wireless charging systems with other rectifier or compensation network topologies etc. They will be helpful for system design and control to make EV wireless charging systems achieve stable operation and high performance.

REFERENCES

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

[2] Y. D. Ko, and Y. J. Jang, "The optimal system design of the online electric vehicle utilizing wireless power transmission technology," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1255-1265, Sep. 2013.

[3] W. X. Zhong, and S. Y. R. Hui, "Maximum energy efficiency tracking for wireless power transfer systems," *IEEE Trans. Power Electron.*, vol. 30, no. 7, pp. 4025-4034, Jul. 2015.

[4] D. Ahn, S. Kim, J. Moon, and I. K. Cho, "Wireless power transfer with automatic feedback control of load resistance transformation," *IEEE Trans. Power Electron.*, vol. 31, no. 11, pp. 7876-7886, Nov. 2016.

[5] Lili Qu1,[1] , Bo Zhang[2] "Research of PWM Converter Control Method in Electric Vehicle" IEEE Vehicle Power and Propulsion Conference (VPPC), September 3-5, 2008, Harbin, China.

[6] "IEEE Access™ Editorial Board." *IEEE Access*, Institute of Electrical and Electronics Engineers (IEEE), 2022, pp. i–x. *Crossref*, doi:10.1109/access.2022.3141347.

[7] Zicheng Bi, Tianze Kan.'' A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility"Applied Energy,Volume 179,2016,Pages 413-425,ISSN 0306-2619,https://doi.org/10.1016/j.apenergy.2016.07.003.

[8] D. Thenathayalan, and J. H. Park, "Wide-air-gap transformer model for the design-oriented analysis of contactless power converters," *IEEETrans. Ind. Electron.*, vol. 62, no. 10, pp. 6345-6359, Oct. 2015.

[9] M. Fu, Z. Tang, M. Liu, C. Ma, and X. Zhu, "Full-bridge rectifier input reactance compensation in megahertz wireless power transfer systems," in *Proc. 2015 WoW*, 2015, pp. 1-5.

[10] A. Berger, M. Agostinelli, S. Vesti, J. A. Oliver, J. A. Cobos, and M. Huemer, "A wireless charging system applying phase-shift and amplitude control to maximize efficiency and extractable power," *IEEE Trans.Power Electron.*, vol. 30, no. 11, pp. 6338-6348, Nov. 2015.

[11] K. Colak, E. Asa, M. Bojarski, D. Czarkowski, and O. C. Onar, "A novel phase-shift control of semi bridgeless active rectifier for wireless power transfer," *IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6288-6297, Nov. 2015.

[12] Y. Akihara, T. Hirose, S. Masuda, N. Kuroki, M. Numa, and M. Hashimoto, "Analytical study of rectifier circuit for wireless power transfer systems," in *Proc. ISAP*, 2016, pp. 338-339.

[13] S. A. Akintade*, Y. Jibril. " Development of Shunt Active Power Filter for Harmonic Reduction using Synchronous Reference Frame with Space Vector Pulse Width Modulation" nigerian journal of technological development, vol. 17, no. 2, june 2020.

[14] H. C. Li, K. P. Wang, L. Huang, W. J. Chen, and X. Yang, "Dynamic modeling based on coupled modes for wireless power transfer systems,"*IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6245-6253, Nov. 2015.

[15] S. Aldhaher, P. C. K. Luk, K. E. K. Drissi, and J. F. Whidborne,"High-input-voltage high-frequency class E rectifiers for resonant inductive links," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp.328-1335, Mar. 2015.

[16] [H. T. Shi, J. D. Mao, X. S. Li, and J. T. Pan, "Modeling and analysis of impedance for uncontrolled rectifier based nonlinear load," in *Proc.CCDC*, 2016, pp. 1770-1775.

[17] C. K. Lee, S. Kiratipongvoot, and S. C. Tan, "High-frequency-fed unity power-factor AC-DC power converter with one switching per cycle,"*IEEE Trans. Power Electron.*, vol. 30, no. 4, pp. 2148-2156, Apr. 2015.

[18] Q. Lei, M. Shen, V. Blasko, and F. Z. Peng, "A generalized input impedance model of three phase diode rectifier," in *Proc. APEC*, 2013, pp.2655-2661.

[19] [S. Q. Li, W. H. Li, J. J. Deng, T. D. Nguyen, and C. C. Mi, "Adouble-sided LCC compensation network and its tuning method for wireless power transfer," *IEEE Trans. Veh. Technol.*, vol. 64, no. 6, pp.2261-2273, Jun. 2015.

[20] M. Dionigi, M. Mongiardo, and R. Perfetti, "Rigorous network andull-wave electromagnetic modeling of wireless power transfer links,"*IEEE Trans. Microwave Theory Tech.*, vol. 63, no. 1, pp. 65-75, Jan.2015.

[21] A. Costanzo, M. Dionigi, F. Mastri, M. Mongiardo, G. Monti, J. A.Russer, P. Russer, and L. Tarricone, "Conditions for a load-independent operating regime in resonant inductive WPT," *IEEE Trans. MicrowaveTheory Tech.*, vol. 65, no. 4, pp. 1066-1076, Apr. 2017.

[22] Q. W. Zhu, L. F. Wang, and C. L. Liao, "Compensate capacitor optimization for kilowatt-level magnetically resonant wireless charging system," *IEEE Trans. Ind. Electron.*, vol. 61, no. 12, pp. 6758-6768, Dec.2014.

[23] J. W. Kim, D. H. Kim, and Y. J. Park, "Analysis of capacitive impedance matching networks for simultaneous wireless power transfer to multiple devices," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 2807-2813, May2015.

[24] J. Kim, and J. Jeong, "Range-adaptive wireless power transfer usingmultiloop and tunable matching techniques," *IEEE Trans. Ind. Electron.*,vol. 62, no. 10, pp. 6233-6241, Oct. 2015.

[25] W. H. Li, H. Zhao, S. Q. Li, J. J. Deng, T. Z. Kan, and C. C. Mi,“Integrated LCC compensation topology for wireless charger in electric and plug-in electric vehicles,” *IEEE Trans. Ind. Electron.,* vol. 62, no. 7,pp. 4215-4225, Jul. 2015.

[26] J. P. W. Chow, H. S. H. Chung, and C. S. Cheng, “Use of transmitter-side electrical information to estimate mutual inductance and regulate

[27] receiver-side power in wireless inductive link,” *IEEE Trans. Power Electron.,* vol. 31, no. 9, pp. 6079-6091, Sep. 2016.

[28] J. Yin, D. Lin, C. K. Lee, and S. Y. R. Hui, “A systematic approach for load monitoring and power control in wireless power transfer systems without any direct output measurement,” *IEEE Trans. Power Electron.,*vol. 30, no. 3, pp. 1657-1667, Mar. 2015.

[29] Z. H. Wang, Y. P. Li, Y. Sun, C. S. Tang, and X. Lv, “Load detection model of voltage-fed inductive power transfer system,” *IEEE Trans. Power Electron.,* vol. 28, no. 11, pp. 5233-5243, Nov. 2013.

[30] M. F. Fu, H. Yin, X. Zhu, and C. B. Ma, “Analysis and tracking of optimal load in wireless power transfer systems,” *IEEE Trans. Power Electron.,*vol. 30, no. 7, pp. 3952-3963, Jul. 2015.

[31] J. Yin, D. Lin, T. Parisini, and S. Y. R. Hui, “Front-end monitoring of the mutual inductance and load resistance in a series-series compensated wireless power transfer system,” *IEEE Trans. Power Electron.,* vol. 31,no. 10, pp. 7339-7352, Oct. 2016.

