Research on Transmission Characteristics of MCPT System Based on Different Compensation Methods

Xin Li, Xia Jin, and Ruoqiong Li

Abstract—**The Mobile Contactless Power Transmission (MCPT) system has a large leakage inductance on both sides and the mutual inductance is easy to fluctuate during the operation, which makes the transmission power and efficiency of the system relatively low. This paper considers the influence of load change, quality factor and coupling coefficient of the MCPT system in the movable process and theoretically analyzes the power transmission characteristics of the MCPT system. Then the power and efficiency transfer characteristics of the two basic compensation methods and the two composite methods are given. Finally, the influence curves of transmission power with frequency, mutual inductance, load and coupling coefficient *k* under two kinds of composite compensation structures are analyzed. The relationship between coupling coefficient, input quality factor Q_{i0} and transmission characteristics under moving conditions is obtained. Using Pspice simulation experiment, the correctness of the theoretical analysis was verified and TS-P compensation method is more suitable for MCPT system.**

Index Terms—**Mobile contactless power transmission (MCPT), Compensation methods, Transmission power, Transmission efficiency**

About four key words or phrases in alphabetical order, separated by commas, for example, visual-servoing, tracking, biomimetic, redundancy, degrees-of-freedom

I. Introduction

Mobile contactless power transmission (MCPT) is an important branch of ICPT system [1]-[3]. It converts the traditional static contactless power supply into a movable power supply mode and realizes real-time power supply. The online power supply reduces the charging time of battery and improves the efficiency of electrical equipment. Therefore, it has a good development and application prospect in the future. However, since the primary side of the system is laid on the ground without magnetic cores, which greatly reduces the coupling coefficient of the system. In order to solve the problem of low transmission power caused by low coupling coefficients, it must be compensated by an appropriate compensation method.

At present, there are many scholars have studied the compensation structures and power transmission characteristics of contactless power transmission system. In practical applications, in order to improve the transmission efficiency and power transmission capability of the MCPT system, optimizing the resonance parameters and compensation structure of the system are two effective solutions [4]-[10]. Reference [11] studied the reactive power compensation method and the selection method of compensation capacitors in the WPT system. And through MATLAB simulation platform, the factors which affect the system operation when using different compensation methods were analyzed. However, reference [11] did not analyze the characteristics of the system transmission efficiency under different compensation structures, especially the composite compensation topologies, such as LCL, T-S, LCC, etc. For composite compensation structures, reference [12] analyzed the influence of system parameters on output voltage and transmission efficiency, and proposed an LCL-SS type compensation network, which has good adaptability to load and transmission distance changes. And reference [13] studied the LCL type ICPT system and proposed a practical parameter design method. Reference [14]-[18], [19]-[21] respectively studied the power transfer characteristics of different traditional compensation methods and different composite compensation structures and their transmission characteristics. Additionally, in reference [22], the equivalent mathematical model, control method and compensation circuit design of the multi-load MCPT system are studied, but the parameters of the compensation circuit are not analyzed, and the parameters of the system are also not optimized. In view of the problem that the transmission efficiency of the wireless power transmission system is reduced due to change in its own parameters and load uncertainty, the reference [23] proposed a dynamic compensation method that can be applied to various topologies. Although the above references have studied the topology and transmission characteristics of wireless power transmission from different aspects, the effects of coupling coefficient and quality factor change on the transmission efficiency of different compensation methods in MCPT systems have not been studied.

For the low coupling coefficient and transmission

Manuscript received April 26, 2019; revised June 27, 2019. This work was supported by the National Natural Science Foundation of China under Project 51767015, the Gansu Provincial Natural Science Foundation of China (Gansu Provincial Science and Technology Plan) under Project 18JR3RA117, the Lanzhou Jiaotong University-Tianjin University Joint Innovation Fund Project2019051.

Xin Li is now with the Department of New Energy & Power Engineering, Lanzhou Jiaotong University, China. (e-mail: lxfp167@ 163.com).

Xia Jin is now with the Department of Automation & Electrical Engineering, Lanzhou Jiaotong University, China. (e-mail:1554662104 @ qq.com).

Ruoqiong Li is now with the Department of Automation & Electrical Engineering, Lanzhou Jiaotong University, China. (e-mail:liruoqiong26@163.com).

efficiency of the MCPT system, the transmission power and efficiency characteristics under different compensation modes are studied in this paper. Based on the MCPT system of TS-S and TS-P type compensation structures, the influence of the variation of the coupling coefficient *k* and the primary input quality factor Q_{i0} on the transmission efficiency is considered. Finally, using the Pspice circuit simulation platform, the influence of the coupling coefficient variation on the transmission performance of the MCPT system with different compensation modes selected in this paper is analyzed.

II. NOTATION

The notation used in this paper are listed as below.

SYMBOL

V_{i0}	the input voltage of resonant
I_f	primary input current
I_p	primary coupling resonant current
I_s	secondary resonant current
L_f	primary inductance
L_p	primary inductance
L_s	secondary inductance
C_f	primary capacitance
C_p	primary capacitance
C_s	secondary capacitor
ω	angular frequency
ω_0	resonant angular frequency
ω_n	normalized angular frequency
R_L	load resistance
M	mutual inductance
k	coupling coefficient
Q	quality factor
η	transmission efficiency
R_p	internal resistance loss
I_L	load current
Q_{i0}	primary input quality factor
Q_{p0}	primary coupling quality factor
Q_{s0}	secondary quality factor

III. THE RELATIONSHIP OF TRANSMISSION EFFICIENCY UNDER DIFFERENT COMPENSATION METHODS

A. Different Compensation Methods and Transmission Characteristic

The simple structure of the MCPT system is shown in Fig.1. In the MCPT system, the primary side coils are placed along the track and the secondary side coils are placed on the bottom of the locomotive. Compared with the general transmission system, the air gap between the primary and secondary sides of the MCPT system is larger. Therefore, the magnetic leakage phenomenon will be more serious and will cause low transmission power and efficiency. In order to compensate for leakage inductance and improve transmission efficiency, capacitance compensation should be performed on both sides.

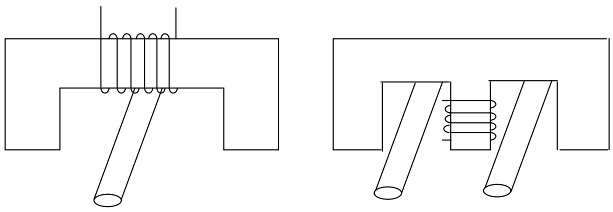

Fig. 1. Schematic diagram of movable contactless power transmission

This paper mainly studies the efficiency characteristics of the MCPT systems with series-series (SS), series-parallel (SP), TS-S and TS-P compensation structures. Four compensation topology circuits are shown in Figure 2. Assuming that the system operating frequency is equal to the resonant frequency, the expressions for the transmission power and efficiency under the above four compensation methods are shown in Table 1-2 [16].

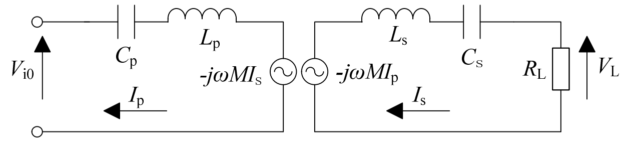

Fig. 2(a). Mutual inductance model of SS typed topology

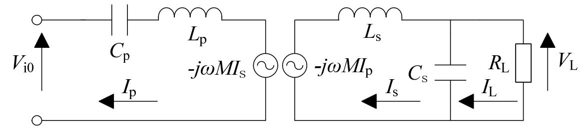

Fig. 2(b). Mutual inductance model of SP typed topology

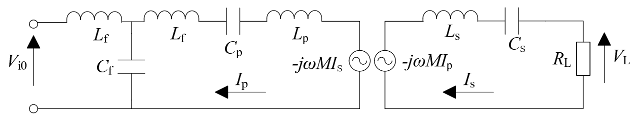

Fig. 2(c). Circuit model of TS-S typed topology

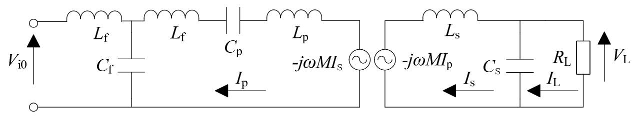

Fig. 2(d). Circuit model of TS-P typed topology

TABLE 1
THE TRANSMISSION POWER OF FOUR KINDS OF COMPEMSATION

compensation method	transmission power expression
series-series compensation	$\dfrac{V_{i0}^2 R_L}{\omega^2 M^2}$
series-parallel compensation	$\dfrac{V_{i0}^2\left(\omega^2 L_s^2 + R_L^2\right)}{M^2\omega^2(R_L+\omega L_s)}$
composite compensation (TS-S)	$\dfrac{L_f^4 R_L}{M^2}$
composite compensation (TS-P)	$\dfrac{V_{i0}^2 M^2 R_L^3}{\omega^4 L_s^4 L_f^2}$

TABLE 2
THE TRANSMISSION EFFICIENCY OF FOUR KINDS OF COMPENSATION

compensation method	transmission efficiency expression
series-series compensation	$\dfrac{\omega^2 M^2}{V_{i0}^2 R_L + R_p}$
series-parallel compensation	$\dfrac{(\omega^2 L_s^2 + R_L^2)R_L^2}{(\omega^2 L_s^2 + R_L^2)R_L^2 M^2 + \omega_0^2 L_s^4 (R_L + \omega L_s) R_p}$
composite compensation (TS-S)	$\dfrac{\omega^2 L_f^6 R_L}{\omega^2 L_f^6 R_L + V_{i0}^2 M^2 R_p}$
composite compensation (TS-P)	$\dfrac{M^2 R_L^3}{M^2 R_L^3 + \omega^2 L_s^4 R_p}$

B. Analysis of Transmission Characteristics for Four Compensation Modes

Since the MCPT system is susceptible to mutual inductance fluctuation and load change, and is prone to frequency bifurcation. According to the MCPT system transmission power expressions of different compensation structures shown in Table 1 and the system parameters shown in Table 3, the influence of system frequency, mutual inductance and load variation on transmission power is obtained as shown in Figure 3-5 by using MATLAB.

TABLE 3
SIMULATION PARAMETERS

Parameter	Value
V_{i0}/V	25.00
L_f/μH	29.56
L_p/μH	550.00
L_s/μH	14.58
R_p/Ω	0.50

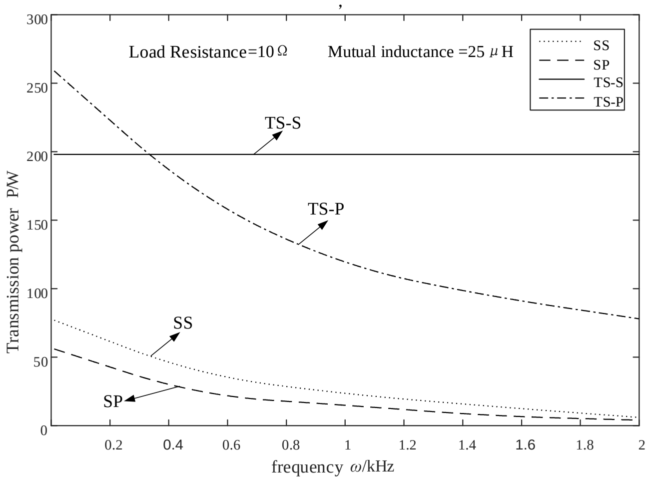

Fig. 3. The variation of transmission power changes with the system frequency

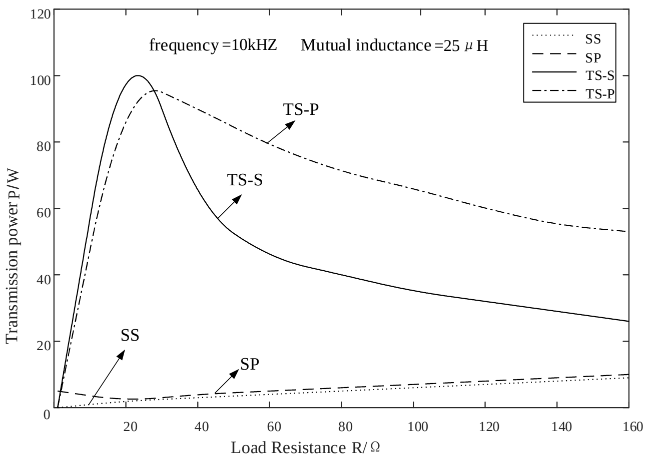

Fig. 4. The variation of transmission power changes with the load

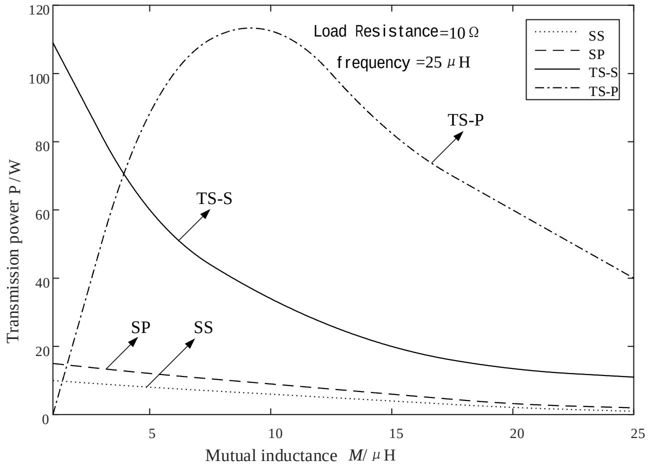

Fig. 5. The variation of transmission power changes with the mutual inductance

As can be seen from Figure 3-5, the transmission power of the MCPT system with T-typed compensation is much larger than that of the system with traditional compensation methods. Specifically, In the TS-S typed compensation mode, when the frequency of the MCPT system changes, its transmission power remains unchanged. The transmission power of the system increases first and then decreases with the increase of the load resistance. The optimal load resistance value that maximizes the transmission efficiency of the system can be obtained. And additionally, the transmission power of the system decreases as the mutual inductance increases. In the TS-P compensation mode, the transmission power of the system decreases with increasing of frequency, so this structure is not suitable for the case where the system frequency is large. And there are optimal load resistance value and mutual inductance value to maximize the system transmission power. The frequency, load resistance and mutual inductance have little effect on the transmission power of the system with traditional compensation structure (SS, SP).

C. Transmission efficiency characteristics of the MCPT systems with different topologies

According to the above analysis, although the transmission power of the SS and SP typed compensation structures is less affected by the frequency, load resistance and mutual inductance change, the transmission power of the two compensation structures is small and cannot meet the practical application requirements. Therefore, only two composite compensation structures are discussed in this section. When the system is in the best resonance state, the parameters of the TS-S and TS-P typed compensation topologies satisfy the following conditions.

$$C_f L_f = C_p L_p = C_s L_s = \frac{1}{\omega_0^2} \tag{1}$$

$$M = k\sqrt{L_p L_s} \tag{2}$$

$$\omega_n = \frac{\omega}{\omega_0} \tag{3}$$

$$Q_{io} = \begin{cases} \omega M^2 / L_f R_L (LCL-SS) \\ M^2 R_L / \omega L_f L_s^2 (LCL-SP) \end{cases} \tag{4}$$

$$Q_{po}=\begin{cases} R_L L_p / \omega M^2 (LCL-SS) \\ \omega L_p L_s^2 / M^2 R_L (LCL-SP) \end{cases} \tag{5}$$

$$Q_{so}=\begin{cases} \omega L_s / R_L (LCL-SS) \\ R_L / \omega L_s (LCL-SP) \end{cases} \tag{6}$$

$$Q_{io}=\frac{L_p}{L_f Q_{p0}} \tag{7}$$

$$Q_{po}=\frac{1}{k^2 Q_{s0}} \tag{8}$$

Let $\alpha = 1/R_L$, and then according to the equations (1)-(8) and efficiency expressions in Table 2, the follow equations can be obtained:

$$\eta_{(LCL-SS)}=\frac{1}{\left(\frac{\alpha}{Q_{i0}}+\frac{\frac{\alpha}{k^2\omega_n^2}}{\frac{Q_{i0}}{k^2\omega_n^2}+\frac{\alpha^2}{Q_{i0}}+\frac{1}{\alpha^2 Q_{i0}}+\frac{\alpha}{k^2\omega_n^2}+\frac{\alpha}{\frac{\alpha Q_{i0}}{k^2\omega_n^2}+\frac{\alpha}{k^2\omega_n^2 Q_{i0}}+\frac{1}{\alpha}}}\right)} \times \frac{1}{\left(\frac{\alpha Q_{i0}}{k^2\omega_n^2}+\frac{\alpha}{k^2\omega_n^2 Q_{i0}}+\frac{1}{\alpha}\right)^2} \tag{9}$$

$$\eta_{(LCL-SP)}=\frac{1}{\left(\frac{\alpha^5 Q_{i0}^3}{\omega_n^4}+\frac{\frac{\omega_n^4}{\alpha^4 Q_{i0}^3}}{\frac{\alpha Q_{i0}}{k^4}+\frac{\alpha^5 Q_{i0}^3}{\omega_n^4}+\frac{\alpha\omega_n^2}{k^2 Q_{i0}^3}+\frac{1}{k^2\omega_n^3 Q_{i0}}+\frac{\alpha^2 Q_{i0}}{\frac{\alpha^3 Q_{i0}^2\omega_n}{k^2}+\frac{\frac{\omega_n^4}{\alpha^4 Q_{i0}^3}}{\frac{\alpha^4 Q_{i0}^3}{k^2\omega_n}+\frac{\alpha^3 Q_{i0}^2\omega_n}{k^2}+\frac{\alpha^3 Q_{i0}^3}{k^2\omega_n^3}}}}\right)} \times \frac{1}{\left(\frac{\alpha^3 Q_{i0}^2\omega_n}{k^2}+\frac{\frac{\omega_n^4}{\alpha^4 Q_{i0}^3}}{\frac{\alpha^4 Q_{i0}^3}{k^2\omega_n}+\frac{\alpha^3 Q_{i0}^2\omega_n}{k^2}+\frac{\alpha^3 Q_{i0}^3}{k^2\omega_n^3}}\right)^2} \tag{10}$$

D. Effect of Coupling Coefficient k on Transmission Efficiency

When the input quality factor of the system Q_{i0}=1 and α=0.1, the influence curves of the coupling coefficient k on the transmission efficiency of the two composite compensation methods are shown in Fig. 6 and Fig. 7, respectively. It can be seen from Fig. 6 and Fig. 7 that the transmission efficiency of these two compensation methods is positively correlated with the coupling coefficient k. The transmission efficiency of the MCPT system with TS-S typed compensation structure is maximum when the normalized frequency ω_n=1. In addition, in an MCPT system with a TS-P compensation structure, the frequency point that maximizes the transmission efficiency changes with the change of the coupling coefficient. Therefore, the system with this compensation structure does not have a fixed frequency point to maximize the transmission efficiency.

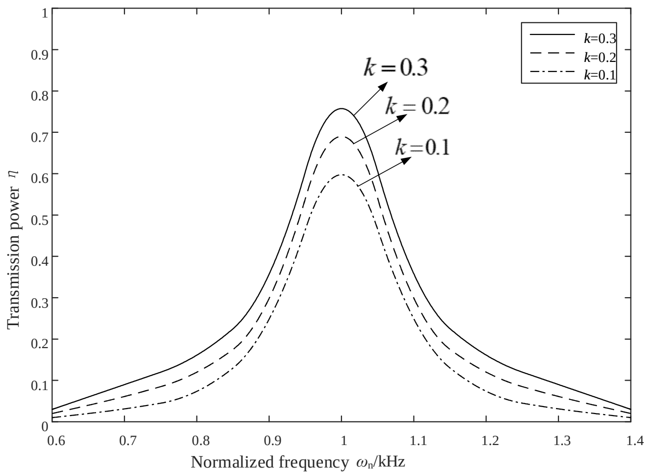

Fig. 6. Transmission efficiency of TS-S typed compensation in different k

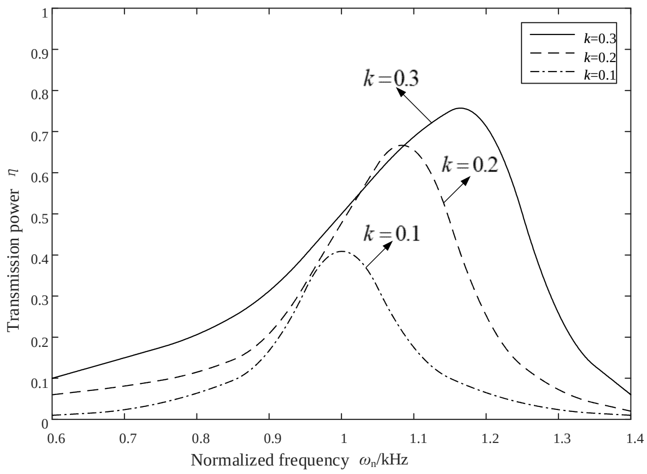

Fig. 7. Transmission efficiency of TS-P typed compensation in different k

E. Effect of Quality Factor Q_{i0} on Transmission Efficiency

When the coupling coefficient k=0.3 and α=0.1, the influence curves of the primary input quality factor Q_{i0} on the transmission efficiency for the two composite compensation methods are shown in Fig.8 and Fig.9 , respectively. As can be seen from Figures 8 and 9, the transmission efficiency of the two compensation methods is positively correlated with the primary input quality factor Q_{i0}. When the system operates at resonant frequency, i.e., $\omega=\omega_0$, the transmission efficiency is maximized under both compensation methods.

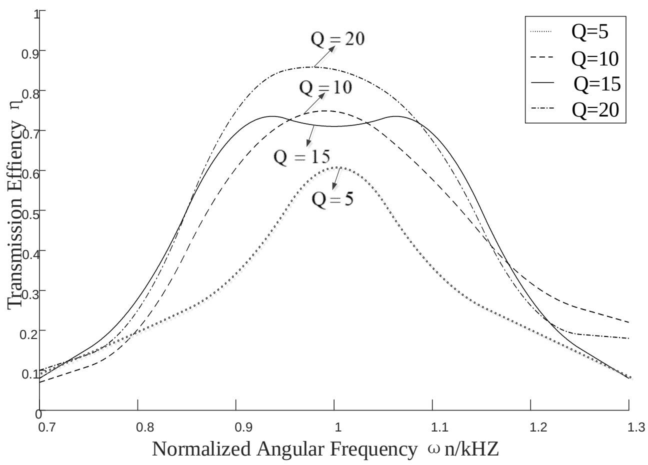

Fig. 8. Transmission efficiency of TS-S compensation in different Q

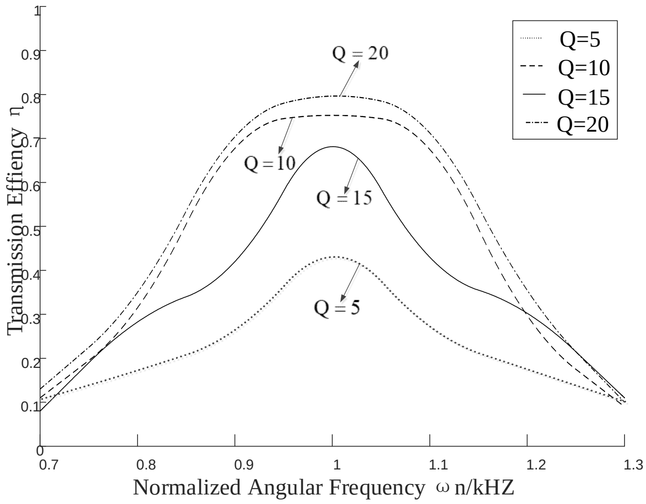

Fig. 9. Transmission efficiency of TS-P compensation in different *Q*

The power transmission efficiency of the MCPT system with TS-S typed compensation structure increases with the increase of the coupling coefficient *k* and the primary input quality factor Q_{i0}, and the efficiency is maximized at the resonance frequency. In the TS-P compensation mode, the frequency of the maximum transmission efficiency varies with the coupling coefficient, but the system is more robust than the TS-S compensation structure. Due to the TS-S typed compensation structure is greatly affected by frequency change, and the frequency of the MCPT system is unstable and prone to frequency bifurcation, so the TS-P compensation method is more practical.

IV. Simulation Verification

To verify the correctness of the above theoretical analysis, Pspice simulation circuit is built as Figure 10-11, and parameters are shown in Table 4.

TABLE 4
PSPICE SIMULATION PARAMETERS

Parament	Value
V_{i0}/V	25.00
L_f/μH	25.93
C_f/μF	1.84
L_p/μ	534.41
C_p/μ	0.09
L_s/μ	23.02
C_s/μF	2.43
R_p/Ω	0.50
f/kHZ	25.00

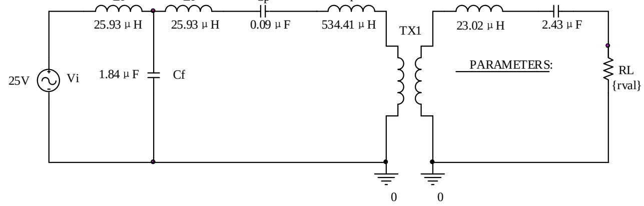

Fig. 10. Simulation circuit of TS-S typed compensation

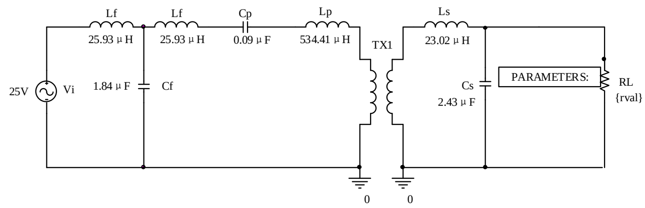

Fig. 11. Simulation circuit of TS-P typed compensation

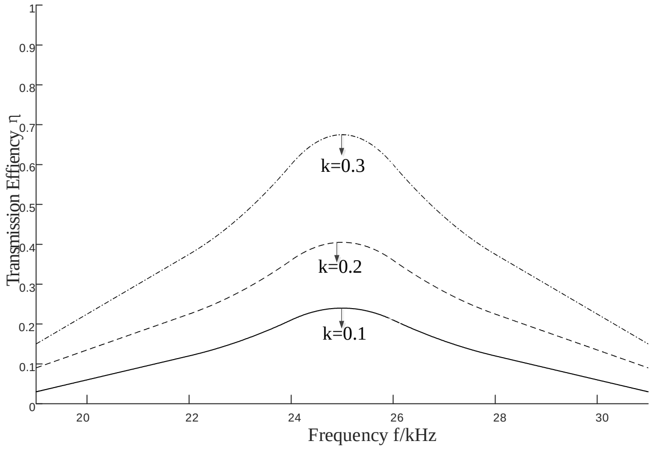

Fig. 12. Transmission efficiency of TS-S compensation in different *k*

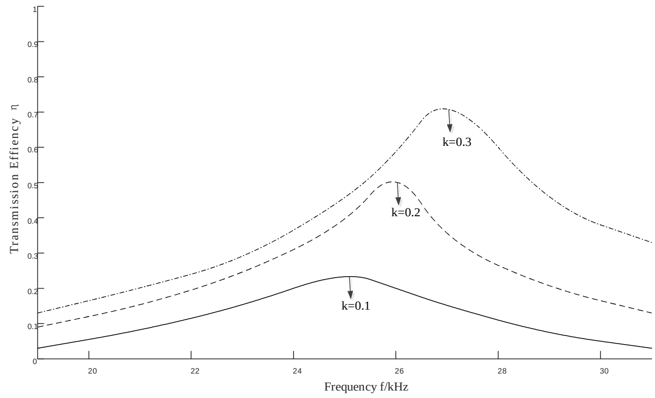

Fig. 13. Transmission efficiency of TS-P compensation in different *k*

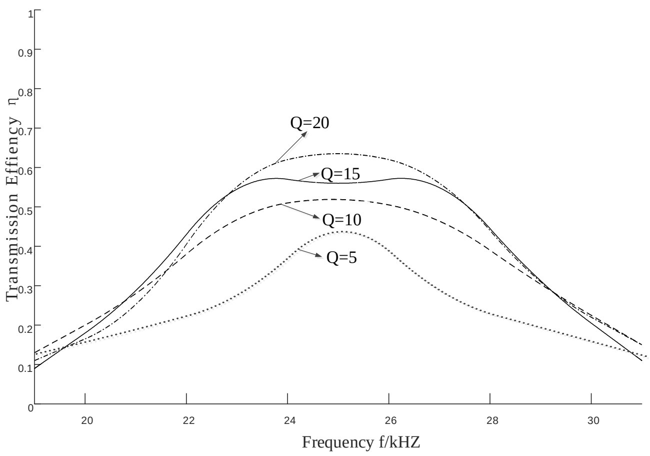

Fig. 14. Transmission efficiency of TS-S typed compensation in different *Q*

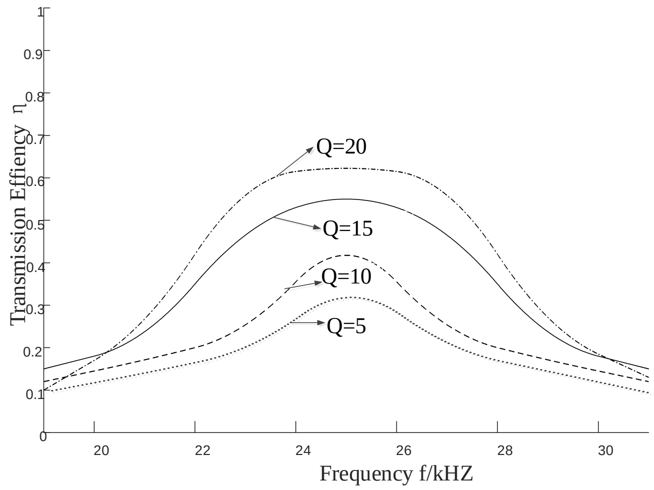

Fig. 15. Transmission efficiency of TS-P typed compensation in different Q

The simulation results are shown in Figures 12-15. It can be seen from the figures that the theoretical analysis and simulation results are basically the same. In simulation experiment, due to factors such as the loss of capacitance and inductance, the transmission efficiency is relatively low compared to theoretical analysis. Furthermore, the transmission efficiency of the TS-S typed and TS-P typed compensation MCPT system is positively related to the coupling coefficient k and the primary input quality factor Q_{i0}. It can be seen that selecting a larger value of the coupling coefficient and the primary side input quality factor can reduce the harmonics of the system, thereby improving the transmission efficiency of the entire system.

V. CONCLUSION

This paper studies the problem of low transmission power and efficiency which causes by the serious leakage inductance of the MCPT system. By analyzing the transmission characteristics of the four different compensation modes, the following conclusions can be drawn:

(1) The transmission power of the MCPT system with traditional compensation structures changes slowly with the change of frequency, load and mutual inductance. The transmission power of the T-typed composite compensation structures is much larger than that of the traditional compensation methods. The transmission efficiency of MCPT system with TS-S typed compensation mode increases first and then decreases as the load resistance and mutual inductance increase. In addition, In the TS-P typed compensation mode, when the system parameters are reasonably configured, the system efficiency can reach the maximum.

(2) The transmission efficiency of the TS-S typed and TS-P typed compensation structures increases as the coupling coefficient k increases. There is no fixed frequency when the system with TS-P typed compensation structure reaches the maximum transmission efficiency. The TS-S compensation method is more suitable for the case where the system frequency does not change.

(3) Both the transmission efficiency of the TS-S typed and TS-P typed compensation structures increase with the increase of the primary input quality factor Q_{i0}. It can be seen that a larger Q_{i0} can improve the transmission efficiency of the entire system and reduce system harmonics. As far as the coupling coefficient is concerned, the TS-P typed compensation method has better robust performance than the TS-S typed compensation method.

(4) Through theoretical analysis and simulation experiment, the TS-P compensation structure is more suitable for mobile non-contact power supply system.

REFERENCES

[1] X. Dai, Y. Sun, Y. G. Su, et al., "Study on contactless power bi-directional push mode," *in Proceedings of the CSEE*, vol. 30, no.18, pp.55-61, 2010.
[2] H. B. Zhang, A. H. He, A.L. Zou, et al., "Research about a movable ICPT system with muti-load," *Power Electronics*, vol. 48, no. 3, pp. 48-50, 2014.
[3] H. Wang, X. Li, "Review and research progress of wireless power transfer for railway transportation," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 14, no. 3, pp. 475-484, 2019.
[4] H. L. LI, A. P. HU, G. COVIC, et al., "Optimal coupling condition of IPT system for achieving maximum power transfer," *Electronics Letters*, vol. 45, no. 1, pp. 76-77, 2009.
[5] J. Sallan, L. Villa, A. Llombart, et al., "Optimal design of ICPT systems applied to electric vehicle battery charge," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 2140-2149, 2009.
[6] Z. Pantic, S. Ehattacharya, S. Lukic, "Optimal resonant design considerations for primary track compensation in inductive power transfer systems," *Energy Conversion Congress and Exposition, Atlanta, GA, USA, IEEE*, pp.1602-1609, 2010.
[7] Y. Sun, C. Y. Xia, Y. G. SU, et al., "Analysis and optimization of transmission power and efficiency for rail-type contactless power transfer system," *Journal of South China University of Technology Natural Science Edition*, vol. 38, no. 10, pp.123-129, 2010.
[8] Z. B. Zhao, "Parameter optimization of ICPT system based on NLP modeling," Chongqing: Chongqing University, 2012.
[9] A. R. C. Cheah, K. H. Yeap, K. Hirasawa, K. C. Yeong, H. Nisar, "Optimization of a Wireless Power Transmission System," International Multi Conference of Engineers and Computer Scientists, Hong Kong, 2016, pp.16-18.
[10] A. A. Aderemi, O. Ajijola, I. P. Segun, M. O. Victor, "Development of a Wireless Power Transfer System using Resonant Inductive Coupling," International Multi Conference of Engineers and Computer Scientists, Sans Francisco, USA, 2016, pp. 13-18.
[11] J. Huang, Q. Hu, R. Nie, "Modeling analysis for compensation network of contactless power transfer system," *Microcomputer Information*, vol. 25, no. 7, pp. 263-265, 2009.
[12] H. Q. Mo, H. J. Tang, J. Y. Lan, et al.., "Design of wireless power transmission system based on TS-S resonant network," Power Electronics vol. 49, no. 10, pp:34-37, 2015.
[13] K. Yu, "Study of characteristics of LCL-type inductive coupled power transfer system", Chonqing: Chongqing University, 2012.
[14] S. Y. Lin, X. S. Huang, "Modeling and design of TS-S compensation networks for WPT system," *Journal of Fujian University of Technology*, vol. 14, no. 3, pp. 268-273, 2016.
[15] A. P. Sample, D. A. Meyer, J. R. Smith, "Analysis Experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 2, pp.544-554, 2011.
[16] Z. H. Chen, X. X. Zhao, Z. Han, et al., "Research on the Transmission Characteristics of MCPT Power System in Different Compensation Modes," *High Voltage Apparatus*, vol.53, no. 1, pp. 26-31, 2017.
[17] W. Zhang, S. C. Wong, C. K. Tse, et al., "Design for efficiency optimization and voltage controllability of series-series compensated inductive power transfer system," *IEEE Transactions on Power Electronics*, vol. 29, no. 1, pp. 191-200, 2014.
[18] Y. K. Liu, "Investigation of power-efficiency characteristics for wireless power transmission system with different compensation networks," Dalian: Dalian University of Technology, 2014.
[19] W. Q. Zhou, H. Ma, X. Q. He, "Investigation on different compensation topologies in inductively coupled power transfer system," *Transactions of China Electro-technical Society*, vol. 24, no.1, pp.133-139, 2009.

[20] C. Y. Xia, G. Q. Xie, K. Z. Lin, et al., "Study of dual resonance point characteristics and maximum output power of ICPT based on double LCL compensation," *in Proceedings of the CSEE*, vol.36, no.19, pp. 5200-5208, 2016.

[21] M. K. Si, S. R. Wu, X. Zhang, et al., "Research on parallel system of inductively coupled power transfer based on LCL compensation," *Advanced Technology of Electrical Engineering and Energy*, vol. 35, no.4, pp.6-11,2016.

[22] A. L. Zou, H. Z. Wang, J. Hua, "The movable ICPT system with multi-loads based on the LCL compensation circuit," *in Proceedings of the CSEE*, vol. 34, no.24, pp. 4000-4006, 2014.

[23] X. Guo, Inductively coupled wireless power transfer technology based on active compensation [D]. Beijing: Beijing Jiaotong University, 2016.