Analysis and Comparison of SP and S/SP Compensated Wireless Power Transfer System for AGV Charging

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***Abstract*—Wireless power system is an excellent alternative for AGV charging. In order to choose a suitable compensation circuit for wireless power transfer system applied to AGV battery charging, two types of constant voltage output compensation, SP and S/SP topology, are selected and analyzed. The effect of mutual inductance, load and working frequency on the voltage gain is compared, respectively. The results show that S/SP is chosen as the compensation topology of the AGV wireless charging system as its voltage gain can be maintained relatively stable when the parameters change.**

Keywords- wireless power system;compensation topology; AGV.

I. INTRODUCTION

Wireless power transfer (WPT) systems utilizes time-varying electromagnetic fields to transfer energy. It has been widely used in traffic, consumer electronics, underwater, mining equipment, and so on. Compared to the traditional plug-in power supply system, the wireless power transfer system can achieve mechanical and electrical isolation, minimize cable and socket applications, and ensure safe operation in harsh environments [1, 2].

Automated guided vehicle (AGV) has been widely used for cargo handling inside the factory, which greatly reduces the labor burden and improves work efficiency. Traditionally, cable and socket is used to charge the AGV, which is troublesome and unsafe. However, when WPT system is applied, the battery can be allowed to get power automatically over an air gap from a primary coil (buried in the ground) to a secondary coil (mounted underneath the AGV chassis).

One of the challenges in designing a WPT system is determining the compensation topology. At present, the basic compensation topologies are mainly composed of four types: series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP) [3], while some more complex compensation topologies are derived on the basis of these four. The hybrid topology on the primary side is proposed in [4], and can switch between two basic compensation networks to satisfy the constant voltage (CV) and constant current (CC) modes for stationary electric vehicle (EV) charging. In [5], an S/SP constant voltage gain compensation topology is proposed, and, under full compensation, the voltage gain is independent of mutual inductance. In addition to the output characteristics of resonant networks, some scholars have performed research on the primary capacitance [6, 7], input impedance [8], soft switching [9, 10], the system transfer efficiency optimization method [11, 12], and the image impedance matching method [13]. However, most of the above papers only analyze the transfer characteristics of a WPT system based on a selected compensation topology, there is no research about how to choose an appropriate compensation topology for a specific application. So this paper aims to select a suitable compensation circuit of by comparison of the effect of some key parameters on the voltage gain

II. VOLTAGE GAIN OF SP AND S/SP

The equivalent circuit diagram with S/SP and SP topology compensated can be drawn as Fig.1, and the calculation formula of voltage gain of SP and S/SP circuit can be derived, as shown in Tab.I.

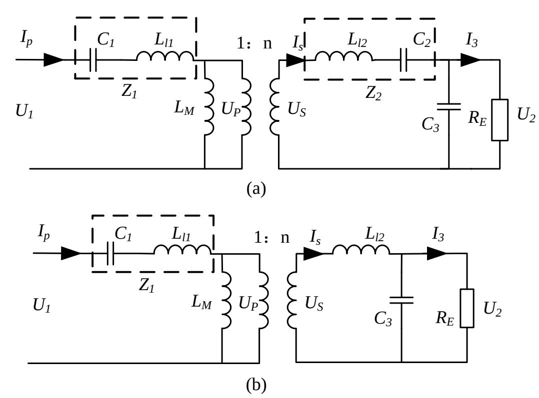

Figure 1. The equivalent circuit diagram with S/SP and SP topology. (a) S/SP. (b) SP.

TABLE I. VOLTAGE GAIN AND COMPENSATION PARAMETERS

Compensation type	Compensation parameters	Voltage gain	Voltage gain at the resonant frequency
SP	$\omega_r = \frac{1}{\sqrt{\left(L_P - \frac{M^2}{L_S}\right) C_1}} = \frac{1}{\sqrt{L_S C_3}}$	$G_{V-SP} = \left\lvert \frac{1}{\frac{\Delta_1}{n\omega^2 L_M C_1} + j\frac{\Delta_2}{\omega n L_M C_1 R_E}} \right\rvert,$ $\Delta_1 = \omega^4 (k^2-1) L_P L_S C_1 C_3 + \omega^2 (L_P C_1 + L_S C_3) - 1$ $\Delta_2 = (\omega^2 L_P C_1 - 1) L_{l2} + n^2 (\omega^2 L_M L_{l1} C_1 - L_M)$	$G_{V-SP}(\omega_r) = \frac{L_S}{M}$
S/SP	$\omega_r = \frac{1}{\sqrt{L_{l1} C_1}} = \frac{1}{\sqrt{L_{l2} C_2}} = \frac{1}{\sqrt{L_M n^2 C_3}}$	$G_{V-SSP} = \left\lvert \frac{n}{\frac{\Delta_1}{j\omega L_M} + \frac{\Delta_2}{j\omega^3 C_1 C_2 L_M R_E}} \right\rvert$ $Z_1 = j(\omega L_{l1} - 1/\omega C_1), Z_2 = j(\omega L_{l2} - 1/\omega C_2),$ $Z_3 = j(\omega n^2 L_M - 1/\omega C_3),$ $\Delta_2 = \omega^4 C_1 C_2 (n^2 L_M^2 - L_P L_S) + \omega^2 (L_P C_1 + L_S C_2) - 1,$ $\Delta_1 = j\omega C_3 [Z_1 Z_3 + (Z_1 + j\omega L_M) Z_2] + j\omega L_M$	$G_{V-SSP}(\omega_r) = n$

I. VOLTAGE GAIN OF SP AND S/SP

The parameters shown in Tab.II are used to analyze the effect of mutual, load and frequency on voltage gain.

TABLE II. COILS PARAMETERS

Parameter	Value
Resonant frequency f (kHz)	22.9
Primary coil inductance L_P (μH)	177.2
Secondary coil inductance L_S (μH)	178.1
Mutual inductance M (μH)	30
Compensation parameters	SSP: C_1=C_2=0.33μF, C_3=1.6 μF SP: C_1=0.28 μH，C_2=0.27 μH

A. *Effect of mutual on voltage gain*

Since there is no mechanical connection between the primary and secondary of the WPT system, the offset of coils and the change of the air gap will cause changes in mutual inductance, which will result in the transfer characteristics, especially voltage gain, changes. As a result, it is necessary to analyze the voltage gain of WPT system with different compensation topology as the mutual inductance changes. The variation of system voltage gain with mutual inductance with S/SP and SP topology adopted is shown in Fig.2.

It can be seen from Fig.2 that when the other parameters of the circuit are unchanged and the mutual inductance value changes from 10 to 50μH, the voltage gain of the two topologies both decreases with the increase of mutual inductance and the voltage gain variation rates of the S/SP topology could be seen as same as that of SP topology. However, when the mutual inductance is equal to 30μH, the voltage gain of SP circuit is about 5.9. When the circuit parameters are determined, even if the voltage gain change rate is small, the absolute value of the voltage magnitude change will be large, which is not conducive to the stable

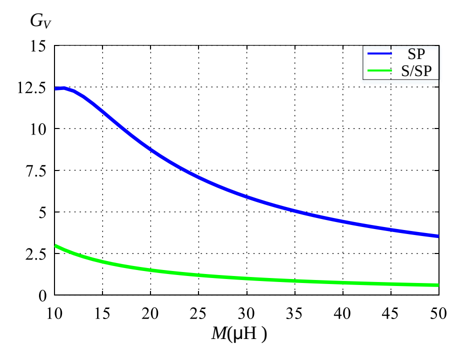

Figure 2. The variation of voltage gain with mutual.

operation of the circuit. This means that the S/SP topology is better from the perspective of the effect of mutual inductance on voltage gain

B. *Effect of load resistance on voltage gain*

When the battery is charged using the three-stage charging method, the equivalent resistance of the system will vary over a wide range. So, the voltage gain varying with load under different mutual inductance values is analyzes next. When the equivalent load R_E is varied from a wide range of 10 to 500 Ω, the curve of voltage gain G_V of S/SP and SP for the mutual inductance M of 20 - 40 μH is shown in Fig.3 (a) and (b), respectively.

It can be obtained by comparing Fig.3 (a) and (b) that with the mutual inductance changed to a certain value, the voltage gain of the two topologies both no longer changes when the load resistance is large. When the load resistance is very small, the voltage gain of S/SP increases slightly with the increase of the resistance, with the voltage gain of the SP compensation mode varying greatly. This means that the SP topology has worse load performance compared to S/SP. At the same time, the SP topology has a large voltage gain, which means that a smaller primary dc voltage but multiplied current is needed at the same output voltage and output power, which is suitable

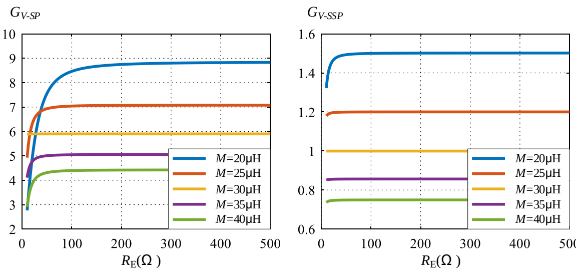

Figure 3. The variation of voltage gain with load. (a) SP. (b) S/SP.

for low input-voltage but high output-voltage applications, and presents higher requirements on circuit components.

C. Effect of frequency on voltage gain

The control strategy could be divided into constant frequency control and phase locked loop control (PLL) according to whether the system working frequency is fixed or not. The PLL control monitors the output voltage and current of the primary inverter, and uses the frequency tracking method to make the primary and secondary sides operate in a resonant state. It can be seen from the analysis in Section II that when the mutual inductance changes, the resonance state of SP and S/SP compensation topology will be affected, so PLL control maybe needed. Next, the influence of frequency change on the voltage gain is analyzed with the other parameters of the system remained unchanged, as shown in Fig.4.

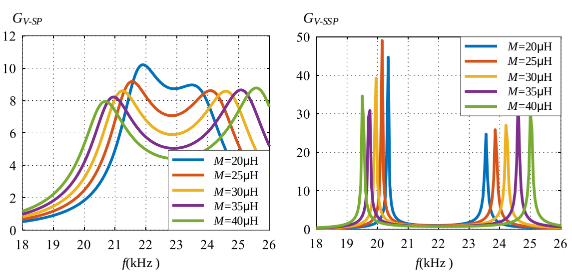

Figure 4. The variation of voltage gain with frequency. (a) SP. (b) S/SP.

It can be seen from Fig. 4 that the voltage gain of both SP and S/SP compensated topology exhibit a frequency bifurcation characteristic, that is, there are two voltage gain spikes, and the peak frequency point of the voltage gain is related to the mutual inductance. When the mutual inductance is small, only a narrow frequency range can ensure that the voltage gain of the system is near the rated value. When the operating frequency is outside this range, the low voltage gain of SP topology could not ensure the system to function properly, and the two very high voltage spikes of S/SP may damage the circuit components. Therefore, from the perspective of ensuring the safe and stable operation of the system, it is better to use fixed frequency control regardless of the compensation topology.

In summary, the voltage gain of the S/SP topology can be relatively stable when the mutual inductance and load change with operating frequency fixed, which is beneficial to the stable and safe operation of the system. Therefore, the S/SP topology is selected as the compensation circuit of the system.

II. Experimental Verification

The experimental platform shown in Fig.5 is used for verification. The parameters of the coupling coils are shown in Tab.II. Buck converter is used to charge 15 18650 batteries connected in series after the secondary rectifier circuit. The battery is charged with a three-stage charging method, where the trickle current is 0.2A, the current of constant current stage is 2A, and voltage of the constant voltage stage is 63V. The experimental results is shown in Fig.6.

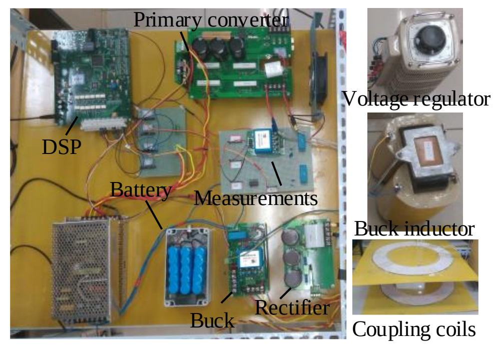

Figure 5. Experimental platform.

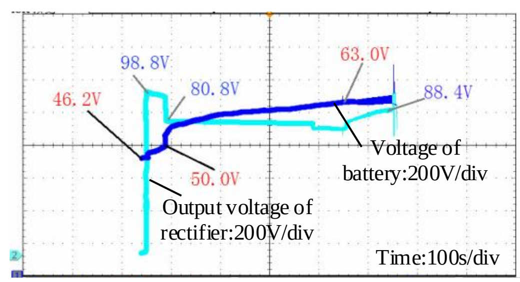

Figure 6. Output voltage of the rectifier and buck converter.

When the three-stage charging method is used to charge the battery and the battery is equivalent to a resistor, its resistance value range is [31.5 250] Ω. Due to the impedance conversion effect of the buck converter, the load chaging range is wider for the rectifier. According to the experimental results, it can be seen that the change of the rectified output voltage is small, about 18V, and the change ratio is about 20%. The experiments verify the correctness of the previous theoretical analysis, that is, the output voltage of the S / SP compensation topology is more stable.

III. Conclusion

This paper first introduces the common model of loosely coupled transformers, and derives the calculating expressions of voltage gain with T model for SP and S/SP topologies. Then, from the perspective of the influence of mutual inductance, load and operating frequency on the system voltage gain, the two constant-voltage-output compensation topologies are analyzed and compared. The results show that S/SP topology can maintain relatively stable when the parameters vary, so it is chosen as the compensation topology of the AGV wireless charging system. The experimental results show that when the load changes in a wide range, the output voltage does not change more than 20%.

REFERENCES

[1] Villa J L, Sallan J, Osorio J F S, et al. High-Misalignment Tolerant Compensation Topology For ICPT Systems[J]. IEEE Transactions on Industrial Electronics, 2012, 59(2):945-951.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] W. Zhang, S. C. Wong, C. K. Tse and Q. Chen, An Optimized Track Length in Roadway Inductive Power Transfer Systems, IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 3, pp. 598-608, Sept. 2014.

[3] Chwei-Sen Wang, Stielau, O.H, Covic, G.A. Design considerations for a contactless electric vehicle battery charger[J]. IEEE Transactions on Industrial Electronics, 52(5):1308-1314.

[4] X. Qu, H. Han, S. Wong, C. K. Tse and W. Chen, Hybrid IPT Topologies With Constant Current or Constant Voltage Output for Battery Charging Applications, IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6329-6337, Nov. 2015.

[5] Hou J, Chen Q, Yan K, et al. Analysis and control of S/SP compensation contactless resonant converter with constant voltage gain[C]// Energy Conversion Congress and Exposition. 2013:2552-2558.

[6] J. Zhao, T. Cai, S. Duan, H. Feng, C. Chen and X. Zhang, A General Design Method of Primary Compensation Network for Dynamic WPT System Maintaining Stable Transmission Power, IEEE Transactions on Power Electronics, vol. 31, no. 12, pp. 8343-8358, Dec. 2016.

[7] H. Feng, T. Cai, S. Duan, J. Zhao, X. Zhang and C. Chen, An LCC-Compensated Resonant Converter Optimized for Robust Reaction to Large Coupling Variation in Dynamic Wireless Power Transfer, IEEE Transactions on Industrial Electronics, vol. 63, no. 10, pp. 6591-6601, Oct. 2016.

[8] J. L. Villa, J. Sallan, J. F. Sanz Osorio and A. Llombart, High-Misalignment Tolerant Compensation Topology For ICPT Systems, IEEE Transactions on Industrial Electronics, vol. 59, no. 2, pp. 945-951, Feb. 2012.

[9] Rengui Lu, Tianyu Wang, Yinhua Mao and Chunbo Zhu, Analysis and design of a wireless closed-loop ICPT system working at ZVS mode, 2010 IEEE Vehicle Power and Propulsion Conference, Lille, 2010, pp. 1-5.

[10] C. S. Tang, Y. Sun, Y. G. Su, S. K. Nguang and A. P. Hu, Determining Multiple Steady-State ZCS Operating Points of a Switch-Mode Contactless Power Transfer System, IEEE Transactions on Power Electronics, vol. 24, no. 2, pp. 416-425, Feb. 2009.

[11] Y. Zhang, K. Chen, F. He, Z. Zhao, T. Lu and L. Yuan, Closed-Form Oriented Modeling and Analysis of Wireless Power Transfer System With Constant-Voltage Source and Load, IEEE Transactions on Power Electronics, vol. 31, no. 5, pp. 3472-3481, May 2016.

[12] W. Zhang, S. Wong, C. K. Tse and Q. Chen, Design for Efficiency Optimization and Voltage Controllability of Series–Series Compensated Inductive Power Transfer Systems, IEEE Transactions on Power Electronics, vol. 29, no. 1, pp. 191-200, Jan. 2014.

[13] M. Dionigi, M. Mongiardo and R. Perfetti, Rigorous Network and Full-Wave Electromagnetic Modeling of Wireless Power Transfer Links, IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 1, pp. 65-75, Jan. 2015.

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