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DESIGN OF MULTI-LOAD WIRELESS POWER TRANSFER SYSTEM WITH SPS AND LCL COMPENSATION TOPOLOGIES

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ABSTRACT: As is common in multi-load wireless power transfer (WPT) systems based on series–series compensation topology, the power received by loads and the efficiency of the process are highly sensitive to changes in the number of loads. Therefore design of a Random Accessed Multi-Load WPT System with Series-Parallel-Series Compensation is proposed in this paper. This uses an LCC/S topology (based on inductor–capacitor–inductor or LCL topology) repeater coils for multiple loads to keep the power received by the loads stable. Each load is connected to a repeater unit and multiple loads can be powered with several repeater units. By comparing two scenarios (ideal and real models based on LCC/S topology), the two coils in the same repeater unit can be placed perpendicularly to eliminate cross-coupling between receiving coils by connecting compensating capacitors in series on the receiving side. The series-parallel-series compensation method is adopted for each repeater unit in order to obtain independent power control of all the loads. This system can guarantee the power supplied to a load remains stable when other loads access or leave the system. Finally, a system to verify our theoretical analysis is established and used to show the validity and effectiveness of the proposed system multi-load WPT system.

KEY WORDS: multi-load wireless power transfer systems, inductor–capacitor–inductor topology, repeater unit, series-parallel-series compensation.

I. INTRODUCTION

AS an epoch-making technique, wireless power transfer (WPT) incredibly realizes the energy migration in a cordless way [1]. This seemingly magic way can change our traditional utilization patterns of the energy in various applications, such as portable electronic devices, implanted medical devices, integrated circuits, solar-powered satellites, electric vehicles (EVs), unmanned aerial vehicles (UAVs) and so forth. By means of its remarkable characteristics of flexibility, position-free and movability, the WPT technique has been taken as an ideal technical solution for energizing electric-driven devices within some specific regions in the near future, especially for smart home applications. The reason why WPT technologies are so crucial is regarding to two fundamental problems of battery-powered devices that limit their popularization - short battery life and high initial cost [2]. Taking EVs as an example, although many automobile manufacturers claim that their products can run over 120 km per charge, when taking into account the range anxiety, most EV drivers only dare to run about 100 km.

On the other hand, by significantly increasing the number of batteries installed in EVs, the driving range can be extended to over 400 km but the corresponding initial cost becomes unaffordable for the general public. Instead of waiting for the breakthrough of energy storage technology, a new energization way, namely the WPT technique, is attracting increasing attentions to bypass the current technical bottlenecks of batteries. By utilizing the WPT technique, battery-powered devices can harness wireless power from electromagnetic field in air and then charge their batteries cordlessly even in the moving state. This novel charging technology can fundamentally solve their problems of short battery life due to limited battery storage or high initial cost due to installation of a large number of batteries.

II. LITERATURE SURVEY

In [2], a modified Helmholtz coil was designed to produce a uniform magnetic field for the improvement of the power stability for powering robotic capsules. In addition, a mixed resonance scheme was also employed to improve the transmission efficiency. In [3], a novel circuit model of the subnominal class-E amplifier was proposed for capsule endoscopes. By analyzing the impact of the amplifier parameters, an optimal subnominal condition was derived for the amplifier design to ensure the high efficiency and safe voltage stress. For millimeter-sized biomedical implants, the energy efficiency can be improved by simply increasing the frequency, while the maximum allowable power is inevitably deteriorated, accordingly.

Misalignment By taking into account the specific absorption rate, an optimal design scheme was proposed by using a high-Q receiving coil and a large external transmitting coil, which can effectively energize the millimeter-sized free-floating implants in a large 3-dimensional space in the neural tissue in [4]. Besides, a coil segmentation technique was proposed to ensure the transmitter voltage at a safe level (~10Vrms) for mid-range WPT systems in [5], which can be used to wirelessly energize a DC pump for artificial hearts or left ventricular assist devices.

In [6], a new figure-of-merit was proposed for the optimal geometry of transmitting and receiving coils under safety constrains, which can strike a balance between the energy efficiency and the maximum transmitted power Varying load. In [7], a triple-loop WPT system was proposed by adopting the closed-loop power control, the adaptive transmitting resonance compensation, and the automatic receiving resonance tuning, which can ensure the maximum the efficiency with respect to varying surrounding environment for implants. By using the PCB pattern coil and the CMOS switch, the parallel resonance topology and associated frequency-tracking scheme were proposed for biomedical implants, which aim to improve the efficiency and maintain a constant output voltage under varying against the variations of the coupling at the load [8].

In order to ensure a motion-free capsule endoscopy inspection, a two-hop WPT system was designed in [9], where the energy is wirelessly transmitted from the transmitting coils beneath the floor to the coil relay embedded in patient's jacket via the strong coupling effect, and then to the capsule via the loose coupling. Additionally, a switch-mode rectifier and a power combination circuit were also developed to improve the energy efficiency for robot capsules. In [10], this paper proposed a frequency control scheme for the primary converter to ensure the transmitted power even if the variations of the load, coupling effect and parameters, which show significant meanings for biomedical implants.

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III. PROPOSED SYSTEM

3.1 System Description

The structure of the proposed multi-load WPT system is shown in Fig. 1. V_0 is the high-frequency power supply. The transmitting coil L_{0_t} is connected with V_0 to transmit power to the subsequent coils, which makes up the transmitting unit #0. There are (N−1) repeater units in Fig. 2, each of which contains two repeater coils, i.e., L_{n_r} and L_{n_t} (n = 1, 2,..., N−1). The letter "r" and "t" in the subscript represent receiving and transmitting, respectively. The number "n" in the subscript indicates the unit number. For example, L_{1_r} is the receiving coil in repeater unit #1. The last unit is the receiving unit #N, where only the receiving coil is needed. In both the transmitting and receiving units, a compensation capacitor (C_{0_t} or C_{N_r}) is connected in series with the corresponding coil, respectively.

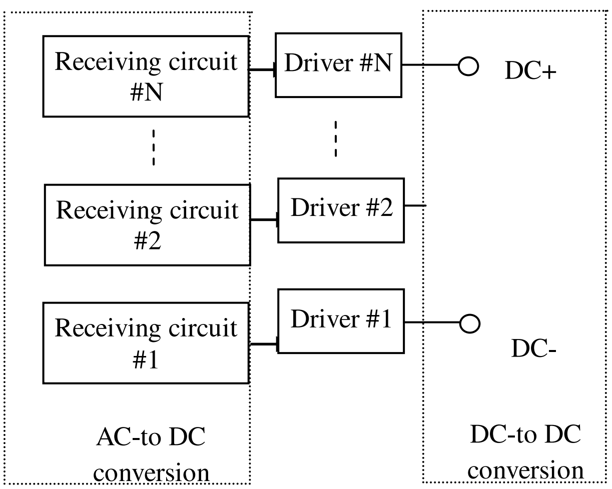

Fig. 1: WPT SYSTEM PROVIDING POWER TO THE DRIVER CIRCUITS IN A MULTILEVEL CONVERTER

3.2 Series-parallel-series compensation Topology

In each repeater unit, three compensation capacitors (C_{n_r}, C_{n_t}, and C_{f_n} where n = 1, 2,..., N − 1) form an SPS compensation topology for the two repeater coils. $I_{0\ t}$, $I_{1\ r}$, $I_{1\ t}$,..., $I_{N\ r}$ are the currents flowing through the corresponding coils. These currents are positive when they flow into the dot terminals of the coils. In order to power the driver circuits for the IGBTs, a receiving circuit consisting of an uncontrolled rectifier and a dc/dc converter to regulate the output power is used to generate a stable dc voltage source for the driver circuit. Considering that the voltage across the rectifier and the current flowing into the rectifier are in phase, the receiving circuit and the driver circuit can be regarded as resistive. Thus, the load is modeled as R_n (n = 1, 2,...,N) for simplification, which is connected in series with the receiving coil in each repeater unit and the receiving unit #N as shown in Fig. 2. With the coil design method in the following section, only the coupling effects between the two adjacent coils in the two adjacent unit, such as L_{1_t} and L_{2_r}, need to be considered. The coupling between other coils, even the two coils in the same unit, can be neglected. The coupling coefficient between unit # (n−1) and #n is defined as

$$k_n = \frac{M_n}{\sqrt{L_{n-1\_t} \cdot L_{n\_r}}} \text{ ---- (1)}$$

Where M_n is the mutual inductance between L_{n-1_t} and L_{n_r} .

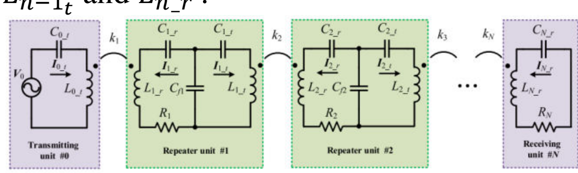

Fig. 2: SPS STRUCTURE OF MULTI-LOAD WPT REPEATER SYSTEM

3.3 LCC Compensation Topology

Figure 3 illustrates an LCL ((inductor–capacitor–inductor)) structure in which $\omega L_t = 1/\omega C_{t\text{-}LCL} = \omega L_{X\text{-}LCL}$ ($L_t = L_{X\text{-}LCL}$) and Z represents an impedance of arbitrary

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magnitude that can be regarded as the total reflected impedance Zref of the WPT system. The computation reveals that no matter how large Z is, the current flowing through the inductor $L_{X\text{-}LCL}$ is always $V_{IN}/j\omega L_{p\text{-}LCL}$. If LCL topology is used for the primary topology of the WPT system, the power load can be guaranteed to be stable when the number of loads changes.

However, to simultaneously supply power to multiple loads in the system, the inductance of the transmitting coil essentially needs to be far larger than that of the receiving coils. Therefore, the coupling between the transmitting coil and the other receiving coils will be enhanced. While a constant current flow through the transmitting coil can be guaranteed using the LCL model, the input voltage of the system V_{IN} is generally designed to be very large in order to meet the power demands of the loads. Therefore, we propose connecting a compensating capacitor C_t in series at the transmitting coil L_t so that an $L_{p\text{-}LCC}$–$C_{p\text{-}LCC}$–$L_{x\text{-}LCC}$ mode is formed in the transmission side of the system ($L_{X\text{-}LCC}$ is used to describe the inductance of the transmitting coil in an LCC structure after the capacitor C_t compensation), i.e., we have an LCC topology, as shown in Figure 3

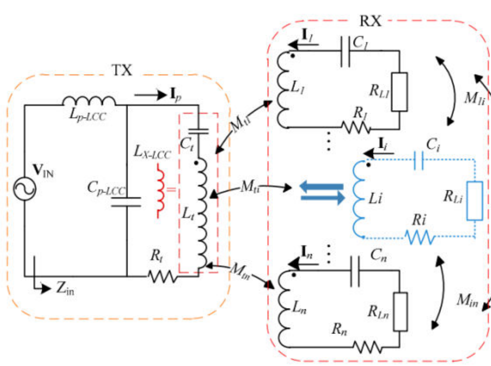

Fig. 3: LLC STRUCTURE OF MULTI-LOAD WPT REPEATER SYSTEM

Where $\omega L_{p\text{-}LCC} = 1/\omega C_{p\text{-}LCC} = \omega L_t - 1/\omega C_t = \omega L_{X\text{-}LCC}$. Therefore, the input impedance Zin can be obtained as:

$$Z_{in} = \frac{\omega^2 \cdot L_{p-LCC^2}}{Z_{ref}+R_t} \text{ ---- (2)}$$

Then, the formula of the input current can be obtained from the input impedance is:

$$I_{in} = V_{in}/Z_{in} = \frac{V_{in}(Z_{ref}+R_t)}{\omega^2 L_{p-LCC^2}} \text{ --- (3)}$$

Finally, the current Ip flowing through the transmitting coil is:

$$I_p = \frac{V_{IN}}{j\omega L_{p-LCC^2}} \text{ ---- (4)}$$

It can be seen that the current flowing through the transmitting coil is independent of the circuit (number of loads) in the receiving side when the topology shown in Figure 3 is adopted, i.e., the current is a constant. Meanwhile, this topology reduces the requirements placed on the supply voltage of the system (for a given demand in power load), simplifies the operating conditions of the system, and also lowers the cost of the system.

3.3. Power Load Optimization in Cross-Coupled Receiving Coils

In practice, the cross-coupling between the receiving coils cannot be ignored. Based on the foregoing analysis, the multi-load WPT system based on LCC/S topology is optimized according to the following two aspects:

(1) Compensating capacitors are connected in series on the receiving side to eliminate cross-coupling between the receiving coils, so as to improve the stability of the load power when the number of loads changes;

(2) The overall efficiency of the system is optimized by designing the load impedance appropriately.

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IV. RESULTS

An experimental setup of the LCC compensation topology based power relay system with six loads has been constructed, as shown in Fig. 4. All the coils are made of the Litz wire to decrease the power loss. PC95 is used as the ferrite material. The film capacitor from KEMET is used to compensate the circuit, which is placed next to the power relay. The dimensions of both the coils and the ferrite plates are the same as in the simulation model. An H-bridge inverter made up of four silicon carbide metal–oxide– semiconductor field-effect transistors (MOSFETs) is adopted to generate a high-frequency ac power source to power the whole system. Considering that the optimal operating frequency of PC95 is from 100 to 300 kHz and the maximum withstand voltage of the compensation capacitor drops dramatically when the frequency exceeds 100 kHz, the operating frequency of the inverter is chosen as 200 kHz. Moreover, if the operating frequency is too high, the system can be easily detuned because of the inductance or capacitance variation during operation. The switching loss will also increase at the higher switching frequency.

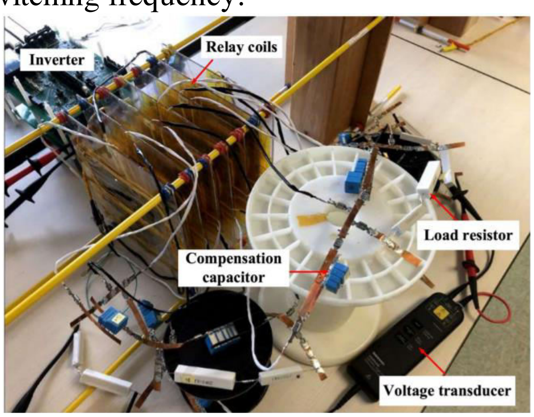

Fig. 4: EXPERIMENTAL SETUP WITH LCC COMPANSETION TOPOLOGY

An experimental setup with ten loads (N = 10) using SPS compensation topology has been constructed as shown in Fig. 5. The coils are fixed on the plexi glass plates. The coupling coefficient k between adjacent units is measured around 0.24. An H-bridge inverter is used to generate a 200kHz ac power supply from a dc source of 30V. The coils' parasitic resistances can be measured using an LCR meter. In our experimental system, the coils' quality factor is around 280.

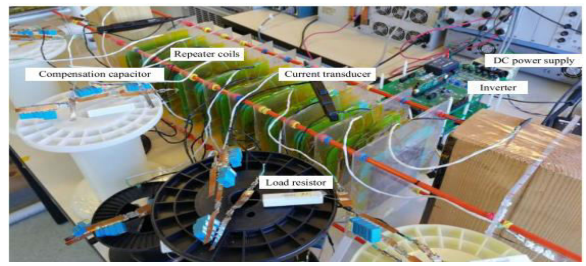

Fig. 5: EXPERIMENTAL SETUP WITH SPS COMPANSETION TOPOLOGY

Fig. 6 shows the load voltage waveforms of SPS compensation topology based WPT system. The inverter's output voltage V0 is almost in phase with I_{0_t} that flows through L_{0_t}. It means that little reactive power exists, which helps decrease the power rating of the inverter. Moreover, I_{0_t} lags a little behind V0. Thus, zero-voltage switching is achieved for the MOSFETs and the switching loss can be greatly decreased. The load voltages V1 and V6 are also given in Fig. 10 that are almost in phase and have the same amplitude.

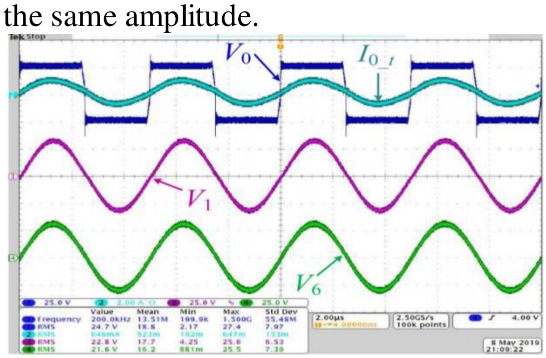

Fig. 6: EXPERIMENTAL LOAD WAVEFORMS OF WITH LCC COMPANSETION TOPOLOGY

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The experimental waveforms are shown in Fig. 5. The current I_{0t} and the input voltage V_0 are nearly in phase so that the input power is nearly all active power. Fig. 7 also shows the waveforms of two load currents I_{1_r} and I_{2_r} . Since the oscilloscope only has four channels, the ten load currents cannot be captured simultaneously in the same figure.

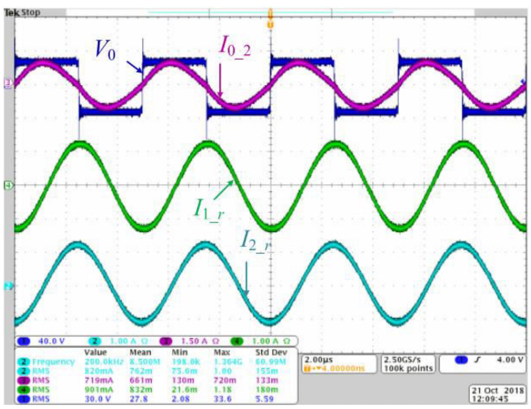

Fig. 7: EXPERIMENTAL LOAD WAVEFORMS OF WITH SPC COMPANSETION TOPOLOGY

V. CONCLUSION

This work is aimed at solving the problem of fluctuations appearing in the power received by loads in a multi-load WPT system based on an S–S topology when the number of loads changes. Thus proposed an improved multi-load WPT system based on based on an LLC and SPS topologies using repeater units, each of which contains two bipolar repeater coils placed perpendicularly. Such topologies guarantee that the power received by the loads is stable. An SPS compensation topology is adopted for each repeater unit. Introducing the LCC topology into the primary side of the WPT system enables one to flexibly adjust the current flowing through the transmitting coil. Moreover, the overall efficiency of the system is also gradually improved. The load is connected in series with the receiving coil in each repeater unit. With the proposed system structure and compensation topology, the constant load currents can be obtained for all the loads. Experimental results are provided to validate the effectiveness of the proposed multiload WPT system

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