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Efficiency Improvement of Wireless Charging System Based on Active Power Source in Receiver

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ABSTRACT Wireless charging technology adapts to the electrified, lightweight, and intelligent trends of electric vehicle development. However, energy efficiency of wireless charging is still lower than conductive charging, and it is important for the wireless charging system to achieve global efficiency optimization in a constant current–constant voltage (CC–CV) charging operation. This paper proposes a novel system configuration, which adds an active power source into the receiver of the wireless charging system. It is proved that the efficiency can be increased significantly with amplitude and phase of the active power source be properly set. A novel current decoupling algorithm is used to analyze the efficiency of the new configuration, and a simulation model is established to validate the theoretical result and to explain the mechanism of efficiency improvement. The simulation shows that the active power source is able to change the power distribution and the current balance, and as a result, the efficiency increases in part of the operating region. The proposed configuration is realized in the experiment and then the efficiency improvement is demonstrated. The experimental result shows that the efficiency increases from 84.9% to 95.7% in a low coupling and slightly detuning working condition.

INDEX TERMS Active power source, electric vehicles, energy efficiency, inductive power transmission, wireless charging.

I. INTRODUCTION

With the promotion of electric vehicle (EV) and continuously increase of energy density of onboard EV battery, charging technology has become an important research field. Conductive charging and wireless charging are two popular charging solutions of EV batteries. Wireless charging can realize automatic charging operation, which performs good applicability for automatic vehicles. Furthermore, wireless charging provides the possibility of ‘‘opportunity charges’’ [1], especially on transit buses. As a result, the onboard battery can achieve downsizing and carbon emissions will be greatly reduced [2], [3]. The Vehicle to Grid (V2G) technology mentioned in [4] has the benefits of buffering the pressure of load demand peak in grid and absorbing fluctuant renewable energy. Wireless charging technology is a viable option for V2G implementation.

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Fig. 1 shows a typical configuration of wireless charging system of EV. It is based on the technology of inductive power transfer. The power from grid is converted to high frequency voltage (79 – 90 kHz for EV [5]). An alternating magnetic field is generated in the primary coil and then a voltage is induced in the secondary coil. The coils of both sides produce a large amount of reactive power, which should be compensated by capacitive networks.

Technical problems of wireless charging are mainly focused on three areas: (1) coil design, (2) compensation topologies, (3) power electronic converters and control methods [1], [6]. Efficiency is one of the most important problem in wireless charging field, because the efficiency of wireless charging is lower than that of conductive charging, especially when the coils are not well aligned. In addition, the electric vehicles are charged in a constant current-constant voltage (CC-CV) operation, as shown in Fig. 2. In the charging process, the equivalent load resistance varies in a large range, especially in CV charging. It makes the wireless charging

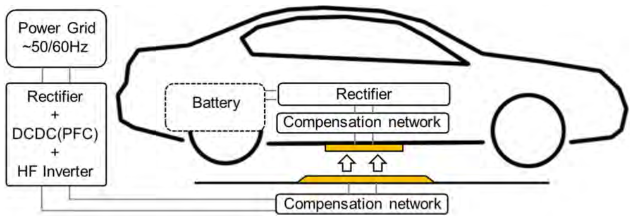

FIGURE 1. Typical wireless charging system configuration of electric vehicle.

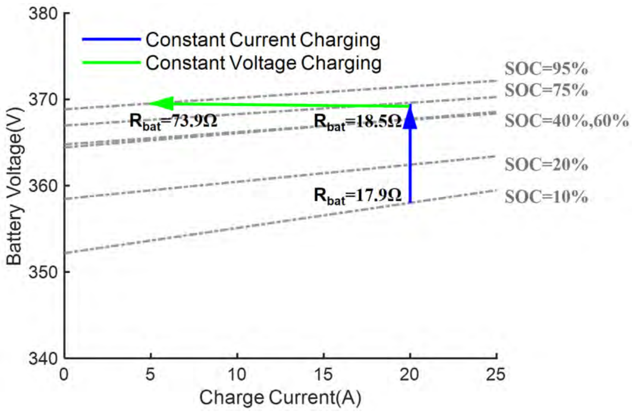

FIGURE 2. Typical charging process and battery characteristics of electric vehicle. In this example, the equivalent load increases from 17.9Ω to 18.5Ω in the CC charging process, and increases from 18.5Ω to 73.9Ω in the CV charging process.

system difficult to achieve global efficiency optimization in the charging operation.

There are two routes to improve the efficiency performance.

The first route is to optimize the system in the design stage, which includes coil design and compensation circuit design. The parameters of coil and magnetic core are modeled and designed for efficiency optimization in [7]–[9]. It is emphasized in [8] that the parameter κQ is vital for coil efficiency. (κ is the coupling coefficient between the coils, and Q is the quality factor of the coils.) The monograph [10] concludes the maximum efficiency and its condition of eight compensation topologies, and many researchers are developing new compensation topologies aiming at achieving high system efficiency.

The second route is to optimize the system in the control stage. For example, phase shift control of the inverter is commonly used in primary side control system. ZVS and ZCS are realized in a phase shift control system to improve the system efficiency in [11]. However, the single-side control is difficult to track the optimal efficiency point. The dual-side control has one more degree of freedom, so the system can satisfy the power requirements and achieve the maximum efficiency at the same time [12].

This paper is aimed at proposing a new system configuration, and realizing efficiency improvement based on this. The content is organized as follows. Section II analyzes the influence factors of coil efficiency. In section III, a new configuration with active power source (APS) in receiver is proposed and its potential of efficiency improvement is analyzed based on theoretical calculation and simulation tool. In section IV, an experimental verification on the proposed configuration is carried out. Section V gives a conclusion of this paper and discusses some problems in the practical use of the new configuration.

II. COIL EFFICIENCY ANALYSIS OF WIRELESS CHARGING CIRCUIT

Whatever the compensation topology is, the power from the primary coil to the secondary coil can be expressed by the following equation [13].

$$P = \omega M I_1 I_2 \sin(\varphi_{12}) \tag{1}$$

where ω is the operating frequency of the circuit, M is the mutual inductance of the two coupling coils, I_1, I_2 are the amplitude of the coil current, and φ_{12} is the phase difference between the two currents.

The coil resistance causes power losses in the wireless power transfer process. If we take R_1, R_2 as the primary coil resistance and the secondary coil resistance, the power loss can be obtained and the coil efficiency η can be approximately calculated as follows.

$$P_{loss} = I_1^2 R_1 + I_2^2 R_2 \tag{2}$$

$$\eta = 1 - \frac{P_{loss}}{P} = 1 - \frac{I_1^2 R_1 + I_2^2 R_2}{\omega M I_1 I_2 \sin(\varphi_{12})} \tag{3}$$

The mutual inductance can be expressed as in (4), where κ, L_1, L_2 are the coupling coefficient and the self-inductance of both sides.

$$M = \kappa\sqrt{L_1 L_2} \tag{4}$$

So the efficiency can be further written as

$$\eta = 1 - \frac{\frac{I_1}{I_2}\sqrt{\frac{R_1}{R_2}} + \frac{I_2}{I_1}\sqrt{\frac{R_2}{R_1}}}{\kappa\sqrt{\frac{\omega L_1}{R_1}\cdot\frac{\omega L_2}{R_2}}\sin(\varphi_{12})} = 1 - \frac{\frac{I_1}{I_2}\sqrt{\frac{R_1}{R_2}} + \frac{I_2}{I_1}\sqrt{\frac{R_2}{R_1}}}{\kappa\sqrt{Q_1 Q_2}\sin(\varphi_{12})} \tag{5}$$

where Q_1, Q_2 are the quality factor of primary and secondary coil. For convenience, we define $Q = \sqrt{Q_1 Q_2}$ as the coil integrated quality factor.

Moreover, the numerator of (5) can be applied to the principle of Cauchy Inequality.

$$\frac{I_1}{I_2}\sqrt{\frac{R_1}{R_2}} + \frac{I_2}{I_1}\sqrt{\frac{R_2}{R_1}} \geq 2 \tag{6}$$

The minimum value can be reached only if

$$\frac{I_1}{I_2}\sqrt{\frac{R_1}{R_2}} = \frac{I_2}{I_1}\sqrt{\frac{R_2}{R_1}}. \tag{7}$$

It can be equivalent to a current balance condition

$$\frac{I_1}{I_2} = \sqrt{\frac{R_2}{R_1}}. \tag{8}$$

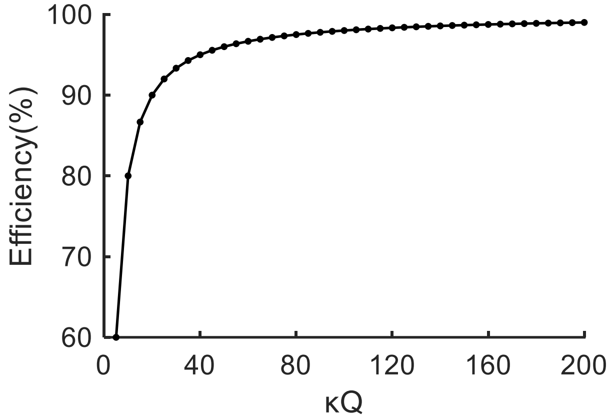

FIGURE 3. Coil efficiency as a function of κQ. In this Fig., sin(φ_{12}) = 1 and the current balance condition (8) is achieved. If a wireless charging system aims at a coil efficiency of 95%, the κQ must be greater than 40.

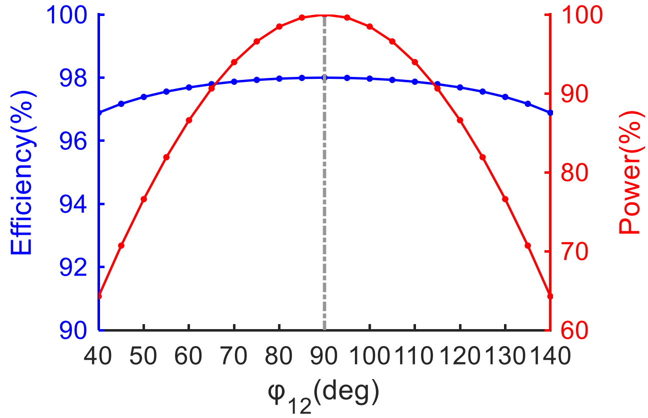

FIGURE 4. Decrease of coil efficiency and power when φ_{12} deviating from 90°. The efficiency drops slightly whereas the power drops obviously. In this Fig., κQ is set to 100 and the current balance condition (8) is achieved, so the maximum efficiency is 98%.

Substitute (6) into (5), we can get

$$\eta \leq 1 - \frac{2}{\kappa Q \sin(\varphi_{12})}. \tag{9}$$

From (9), we can conclude that coil efficiency is affected by three factors.

1) The term κQ is a crucial factor, and it is determined by coil design. Fig. 3 shows the effect of κQ when the other two factors are optimized.
2) Phase difference φ_{12} of the coils. It can be proved in (1) that when power transfers from the primary side to the secondary side, φ_{12} is always in the interval $(0, \pi)$. So $\sin(\varphi_{12})$ is always greater than 0, and the coil efficiency can reach the maximum when $\varphi_{12} = 90°$. Fig. 4 shows the effect of φ_{12}.
3) The current balance of the primary and the secondary. As discussed above, the coil efficiency is maximized when current balance condition (8) is achieved. If the current on both sides deviates from the balance condition, the coil efficiency will decrease, as shown in Fig. 5.

Overall, κQ is a key parameter for the coil efficiency but it can only be improved at the design stage. The phase difference of the coil currents has a quite slight effect on the efficiency in a large scale. The current balance condition is important to the coil efficiency and it can be adjusted by circuit control. However, as described in part I, the load condition varies dramatically in constant current - constant voltage (CC-CV) charging operation, which makes the current balance in the whole CC-CV charging difficult.

III. WIRELESS CHARGING SYSTEM WITH ACTIVE POWER SOURCE IN RECEIVER

A. THE SYSTEM CONFIGURATION

The active power source is introduced in the secondary side of the wireless charging system. It is connected to a single-phase full-bridge inverter, which is called an active inverter. The active power source with the active inverter are equivalent to an ac active voltage source, as shown in Fig. 6, Fig. 7.

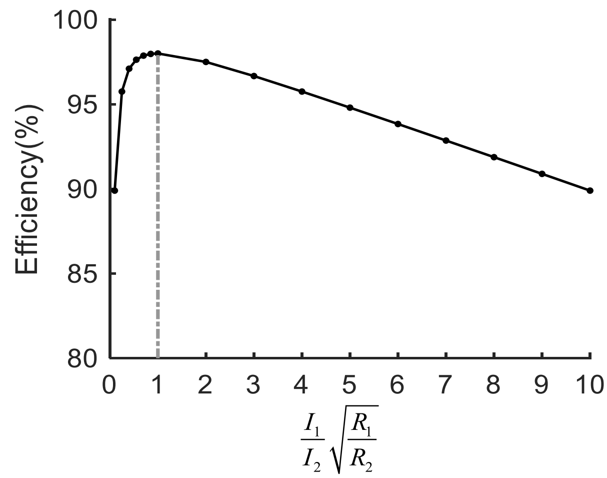

FIGURE 5. The influence of current balance on coil efficiency. In this Fig., sin(φ_{12}) = 1 and κQ is set to 100, so the maximum efficiency is 98%.

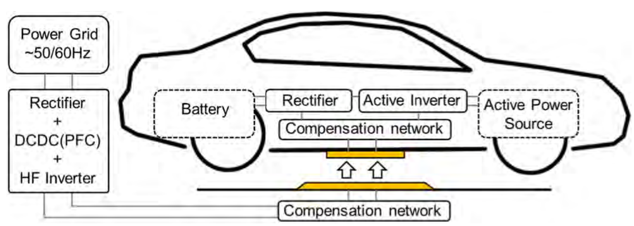

FIGURE 6. Proposed wireless charging system configuration. Active power source with active inverter is connected in series to the system.

The active power source U_A is able to adjust its amplitude and the phase between U_A and the primary power source U_S, by the control of the active inverter. Meanwhile, the active power source is either being charged or discharged. The active power source provides additional degrees of freedom and makes it possible to realize the efficiency improvement.

B. EFFICIENCY CALCULATION OF THE NEW CONFIGURATION

The series-series (SS) compensation topology is widely used in electric vehicle wireless charging system because of its

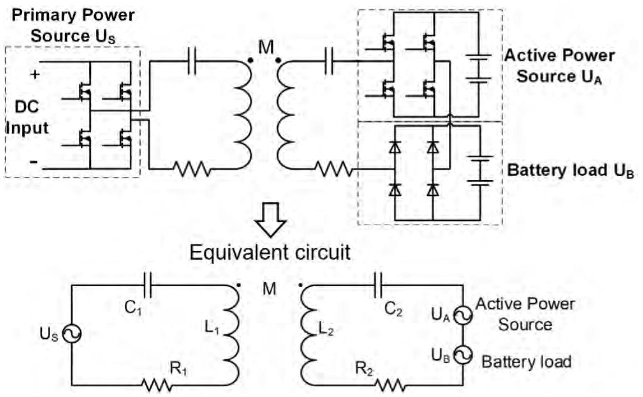

FIGURE 7. **Details and equivalent circuit of proposed wireless charging system. L_1, L_2 are the primary and secondary coil. R_1, R_2 are the coil resistance.**

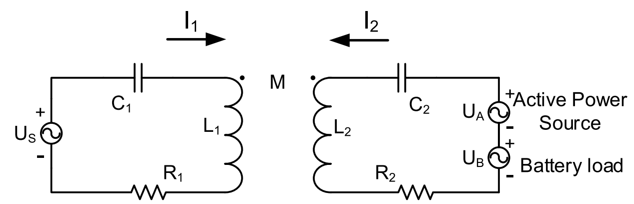

FIGURE 8. **Definition of circuit parameters.**

simplicity, low cost, and the feature of load-independence and coupling-independence [10]. In this paper, the SS topology is applied to analyze the efficiency improvement of the new configuration. However, the conclusion is applicable to other compensation topologies.

The current and voltage direction is defined in Fig. 8. According to the definition of circuit parameters, the circuit equation is given below.

$$\begin{bmatrix} \dot U_S \\ \dot U_A + \dot U_B \end{bmatrix} = \begin{bmatrix} j\omega L_1 + \frac{1}{j\omega C_1} + R_1 & j\omega M \\ j\omega M & j\omega L_2 + \frac{1}{j\omega C_2} + R_2 \end{bmatrix} \begin{bmatrix} \dot I_1 \\ \dot I_2 \end{bmatrix} \quad (10)$$

Assuming that the circuit is in full resonance

$$j\omega L_1 + \frac{1}{j\omega C_1} = j\omega L_2 + \frac{1}{j\omega C_2} = 0. \quad (11)$$

Since the voltage and the current parameters are complex variables, we define that the phase angle of $\dot U_S$ is 0, and other angles are shown in the simplified equation (12).

$$\begin{bmatrix} U_S\angle 0 \\ U_A\angle\alpha + U_B\angle\beta \end{bmatrix} = \begin{bmatrix} R_1 & j\omega M \\ j\omega M & R_2 \end{bmatrix} \begin{bmatrix} I_1\angle i_1 \\ I_2\angle i_2 \end{bmatrix} \quad (12)$$

In (12), U_A and α represents the amplitude and the phase of the complex variable $\dot U_A$, and other complex variables are expressed in the same way. In addition, the battery load is connected to a diode rectifier, which means the phase of $\dot U_B$ is exactly opposite to $\dot I_2$.

$$\angle\beta = 180° + \angle i_2 \quad (13)$$

If we try to use (12) to obtain the expression of the circuit efficiency, that will lead to a series of complex expressions which is difficult to solve, because the currents of primary and the secondary coil are coupled with each other. Hence, a current decoupling algorithm is adopted to get an approximate solution of the efficiency.

The first step of the algorithm is to remove the resistance items and obtain the approximate coil currents $\dot I_{10}$, $\dot I_{20}$. This two currents are decoupled and easy to solve.

$$\begin{bmatrix} U_S\angle 0 \\ U_A\angle\alpha - U_B\angle i_{20} \end{bmatrix} = \begin{bmatrix} 0 & j\omega M \\ j\omega M & P0 \end{bmatrix} \begin{bmatrix} \dot I_{10} \\ \dot I_{20} \end{bmatrix} \quad (14)$$

Solving the current from (14), we get

$$\begin{cases} \dot I_{10} = \dfrac{U_A\angle(\alpha - 90°) + U_B\angle 0}{\omega M} \\ \dot I_{20} = \dfrac{U_S\angle -90°}{\omega M}. \end{cases} \quad (15)$$

The second step is to substitute the approximate current $\dot I_{10}$, $\dot I_{20}$ into the equations with resistance items.

$$\begin{cases} U_S\angle 0 = \dot I_{10}R_1 + j\omega M\dot I_2 \\ U_A\angle\alpha - U_B\angle i_{20} = \dot I_{20}R_2 + j\omega M\dot I_1 \end{cases} \quad (16)$$

And then the modified value of coil currents $\dot I_1$, $\dot I_2$ are obtained.

$$\begin{cases} \dot I_1 = \dfrac{(\omega M U_B + R_2 U_S)\angle 0 + \omega M U_A\angle(\alpha - 90°)}{\omega^2 M^2} \\ \dot I_2 = \dfrac{(\omega M U_S - R_1 U_B)\angle -90° + R_1 U_A\angle\alpha}{\omega^2 M^2} \end{cases} \quad (17)$$

According to the result of coil current, the input power P_S, the output power P_B, and the active power P_A can be calculated. For P_S and P_A, energy output is defined positive, whereas for P_B, energy absorption is defined positive.

$$\begin{cases} P_S = \vec I_1 \bullet \vec U_S \\ \quad = \dfrac{\omega M U_S U_B + \omega M U_S U_A \sin\alpha + R_2 U_S^2}{\omega^2 M^2} \\ P_A = \vec I_2 \bullet \vec U_A \\ \quad = \dfrac{(-\omega M U_S U_A + R_1 U_A U_B)\sin\alpha + R_1 U_A^2}{\omega^2 M^2} \\ P_B = \vec I_2 \bullet \vec U_B \approx \vec I_2 \bullet (U_B\angle i_{20}) \\ \quad = \dfrac{\omega M U_S U_B - R_1 U_A U_B \sin\alpha - R_1 U_B^2}{\omega^2 M^2} \end{cases} \quad (18)$$

In the numerator of the expression of active power P_A, the order of magnitude of $R_1 U_A^2$ is smaller than the other term. As a result, the sign of P_A depends on sinα.

(1) $0° < \alpha < 180°$, $P_A < 0$. The active power source is absorbing energy from the outside, which means it serves as a load. The circuit efficiency can be defined and calculated as follows.

$$\text{define}: \eta = \frac{(-P_A) + P_B}{P_S} (\text{at} P_A < 0) \quad (19)$$

$$\eta = \frac{\omega M\left(1 + \frac{k_A}{k_B}\sin\alpha\right) - \left(\frac{k_A^2}{k_B} + 2k_A\sin\alpha + k_B\right)R_1}{\omega M\left(1 + \frac{k_A}{k_B}\sin\alpha\right) + \frac{R_2}{k_B}} \quad (20)$$

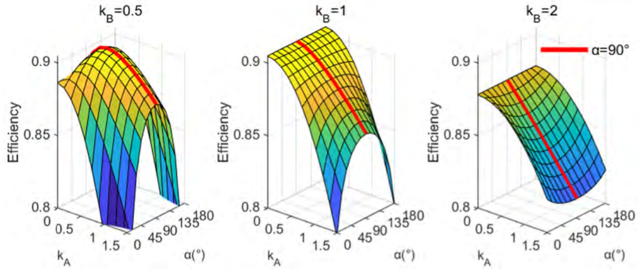

FIGURE 9. Efficiency when the active power source works as a load. In this Fig., $\omega M/R_1 = \omega M/R_2 = 20$. It can be concluded that when $\alpha = 90°$ the efficiency get local maximum or minimum.

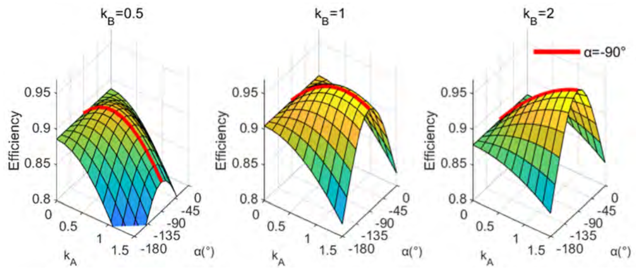

FIGURE 10. Efficiency when the active power source works as a power source. The value of R_1, R_2, and ωM are the same as Fig. 9.

In (20), $k_A = U_A/U_S$, $k_B = U_B/U_S$. Fig. 9 shows the surface plot of efficiency with k_B fixed at different values.

Here are several conclusions from Fig. 9. The efficiency at $k_A = 0$ means the efficiency of wireless charging system without active power source. When $k_B = 1$ or $k_B = 2$, the efficiency declines because of current unbalance. However, when $k_B = 0.5$, appropriate active power source can improve the efficiency when $\alpha = 90°$, $0 < k_A \leq 1.2$.

(2) $-180° < \alpha \leq 0°$, $P_A > 0$. The active power source is providing energy to the outside. The circuit efficiency can be defined and calculated as follows.

$$\text{define}: \eta = \frac{P_B}{P_S + P_A}(\text{at} P_A > 0) \tag{21}$$

$$\eta = \frac{\omega M - k_B R_1 - k_A (\sin\alpha) R_1}{\omega M + \frac{R_2}{k_B} + k_A \left(\frac{k_A}{k_B} + \sin\alpha\right) R_1} \tag{22}$$

Since $\sin\alpha$ in (23) is negative, the efficiency can be improved comparing to the situation without the active power source. Fig. 10 shows the efficiency improvement with k_B fixed at different values.

We can observe that the efficiency can all be improved at $\alpha = 90°$ and proper k_A. The efficiency improves obviously when $k_B = 1$ and $k_B = 2$.

C. EFFICIENCY VALIDATION VIA CIRCUIT SIMULATION

A circuit simulation is established to verify the efficiency calculation result. We use the MATLAB/Simulink to establish the circuit model, as shown in Fig. 11. The power electronics are replaced by signal source with Simulink-PS converter, as the converter efficiencies are not included in this paper. Table 1 shows the values of parameters in the model.

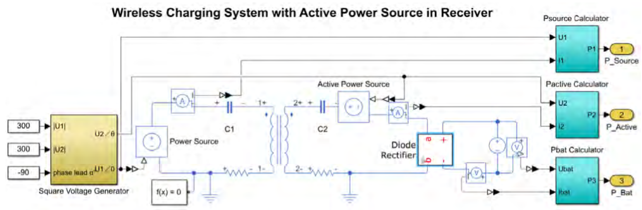

FIGURE 11. Simulink model of proposed wireless charging system.

TABLE 1. Values of parameters in the simulation.

Parameter	Value	Reason
Coil self-inductance	$L_1 = L_2 = 64\mu H$	data from experiment
Compensation Capacitance	$C_1 = C_2 = 52.5nF$	data from experiment
Coil resistance	$R_1 = R_2 = 0.15\Omega$	data from experiment
Coupling coefficient	$\kappa = 0.165$	data from experiment
Operating frequency	$f = 86826Hz$	resonant frequency
Power source voltage	$U_S = 300V$	typical value of EV wireless charging system
Battery voltage	$U_B = 300V$	typical value of EV battery

The voltage and the phase angle of the active power source are altered and in this way efficiency validation is carried out.

Fig. 12 shows a running instance when $U_A = 150V$ and $\alpha = -90°$. In this instance, $P_S = 6.67kW$, $P_A = 6.25kW$, $P_B = 12.49kW$, the efficiency

$$\eta = \frac{P_B}{P_S + P_A} = \frac{12.49}{6.67 + 6.25} = 96.7\% \tag{23}$$

The efficiency analysis result in (20) and (22) is validated by this simulation model. The result is shown in Fig. 13.

The errors between simulation and theoretical calculation are less than 1%. The error may be caused by the calculation approximation in the current decoupling algorithm.

D. ANALYSIS OF EFFICIENCY IMPROVEMENT MECHANISM

There are two aspects of the efficiency improvement mechanism in the proposed wireless charging system.

First, the active power source can change the power distribution. As shown in Fig. 14, when α is set to $-90°$, the APS is providing power to the battery. The output power is almost constant whatever the voltage of active power source (or k_A) is. The more battery energy comes from the APS, the less energy is transferred from the primary side. As a result, losses of primary coil are reduced. However, when $k_A > 1$, the input power P_S turns negative which means the energy from APS transfers to the primary side reversely. As a result, the primary coil losses increase again and the efficiency decreases accordingly.

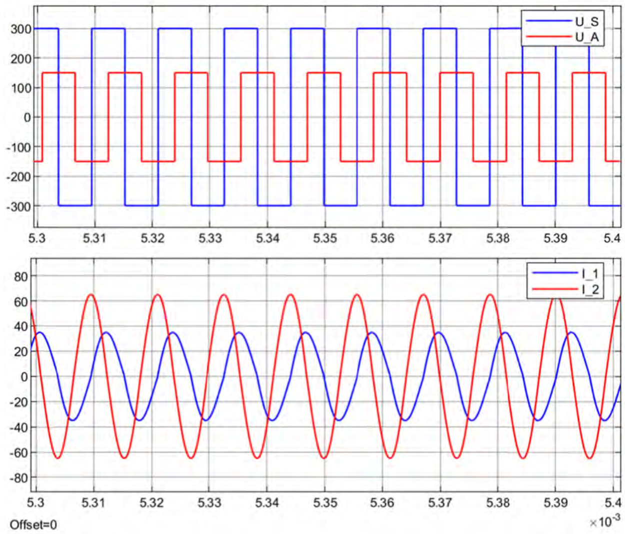

FIGURE 12. **Running instance of the circuit simulation.**

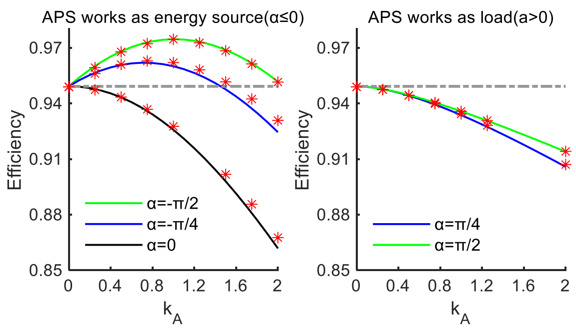

FIGURE 13. **Efficiency validation via Simulink model. The curves are from (20) and (22) at $k_B = 1$, and the scatter is from simulation result. The dashed line represents the efficiency of the wireless charging system without active power source.**

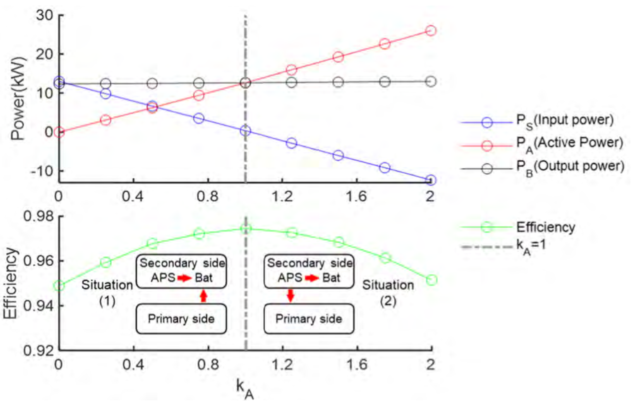

FIGURE 14. **Relation between power distribution and efficiency improvement. This Fig. is obtained from the simulation data at $U_S = U_B = 300V, \alpha = -90°$.**

The second aspect of the efficiency improvement mechanism is that the active power source can improve the current balance. In order to explain this mechanism, another simulation instance ($U_S = 400V$, $U_B = 200V$) is shown in Fig. 15. In this instance, the initial current is not balanced because $U_S > U_B$. So the APS is operated at $\alpha = 90°$ to work as

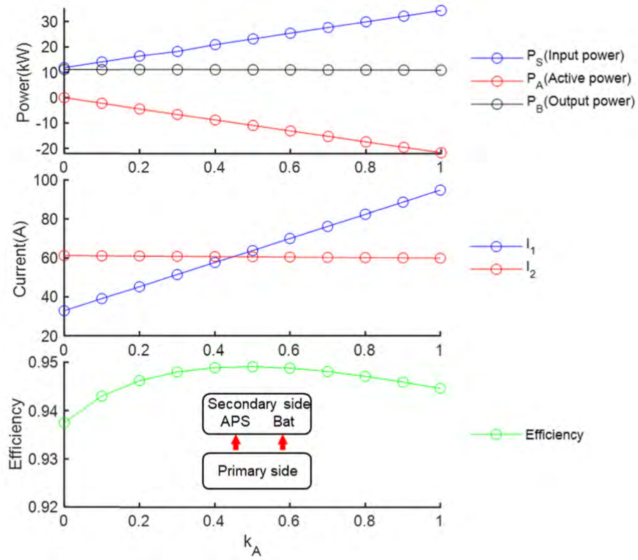

FIGURE 15. **Relation between circuit balance and efficiency. This Fig. is obtained from the simulation data at $U_S = 400V$, $U_B = 200V$, $\alpha = 90°$.**

a load. As the voltage of APS increases, the primary current I_1 also increases. As a result, the current balance is improved and the efficiency rises. When the primary current exceeds the secondary current, the efficiency drops accordingly.

In conclusion, the active power source have two potentials for efficiency improvement: change of power distribution and improvement of the current balance. As for the first aspect, the efficiency improvement only occurs when the active power source provides energy to the outside. For the second aspect, the efficiency can be improved when the active power source works as either a load or a power source. It depends on whether the current difference is reduced.

IV. EXPERIMENT VALIDATION OF WIRELESS CHARGING SYSTEM WITH ACTIVE POWER SOURCE

In order to verify the theoretical analysis results, it is necessary to build a wireless charging experimental system with active power source and carry out experimental verification.

A. INTRODUCTION OF EXPERIMENTAL SYSTEM

The experimental system consists of two components: the power transfer circuit and the test equipment.

As shown in Fig. 16, the power transfer circuit includes two batteries, two inverters, coils, resonant capacitors and a load resistor. The batteries are 12V lead-acid battery which can provide nearly constant DC voltage output. The two batteries with two inverters work as primary power source and active power source respectively. A common inverter controller is used to set the frequency and the phase of the two inverters. The screen of the controller is shown in Fig. 17. The square coils without magnetic core are used since that the coil design do not influence the efficiency validation. The parameters are defined in Fig. 16 and given in Table 2.

The test equipment includes a power analyzer PW6001, an impedance analyzer IM3570, an oscilloscope, and an acrylic test bench. The entire experimental system shows in Fig. 18.

TABLE 2. Values of parameters in the experiment.

Parameter	Value
Coil dimension and turns	40cm*40cm, n=8
Coil self-inductance	$L_1 = 64.41\mu H$, $L_2 = 63.2\mu H$
Coil resistance	$R_1 = 128\text{m}\Omega$, $R_2 = 131\text{m}\Omega$
Compensation Capacitance	$C_1 = 56nF$, $C_2 = 55.9nF$
Distance and misalignment	d=15cm, x=20cm
Coupling coefficient	$\kappa = 0.083$
Operating frequency	$f = 85kHz$
Load Resistance	$R_L = 8\Omega$

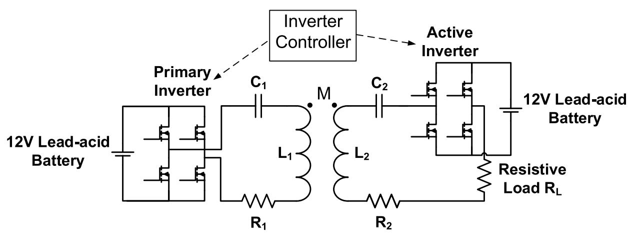

FIGURE 16. The power transfer circuit in experiment.

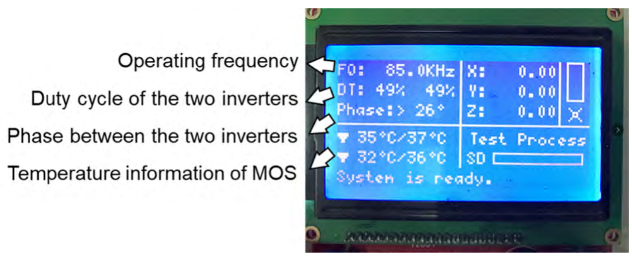

FIGURE 17. The screen of the inverter controller.

B. EXPERIMENTAL VALIDATION

In the experiment, a resistor, rather than a battery, is used as the load. Moreover, the system does not work exactly at the resonant point, and the coupling of coils is low because of a deliberate misalignment. That means the efficiency equations (20) and (22) are not applicable to this experiment. However, the efficiency improvement can still be observed and the two mechanisms explained above are still applied to the experiment.

Fig. 19 shows waveforms from the experiment, and the result of the experiment is shown in Fig. 20.

The experiment of system without APS is done first, and the efficiency without APS is 84.9%. In the experiment of system with APS, the voltage of active power source is fixed and the phase angle is adjusted from $-180°$ to $180°$. When the phase angle varies, the active power source influences the power distribution and the current balance at the same time. When $\alpha = -68°$, the efficiency gets its maximum 95.7%. At this point, the active power source is providing energy to the load, and 45% of the load power is from the active power source. At the same time, the current balance is also improved, which is beneficial to the efficiency improvement.

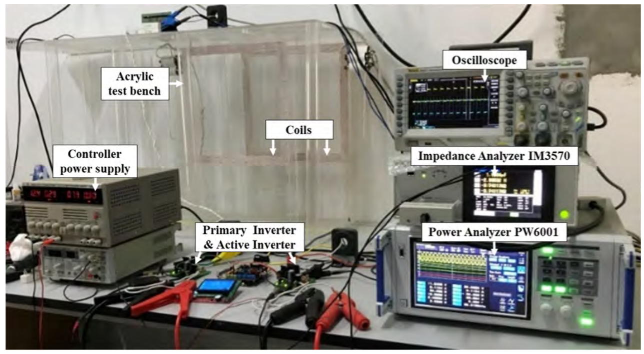

FIGURE 18. The whole picture of the experimental system.

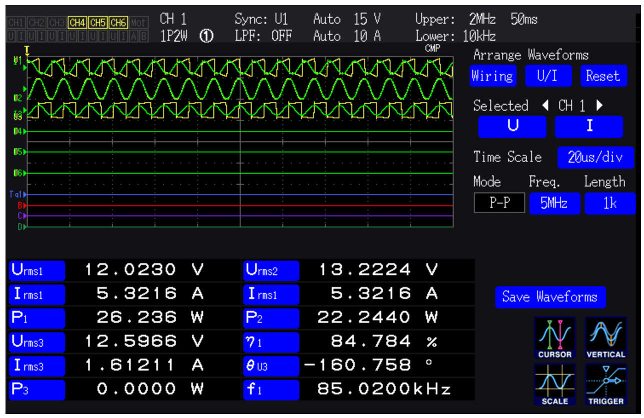

FIGURE 19. Experiment waveforms of the system. The first channel measures the input power, the second channel measures the output power, and the third channel measures the active power.

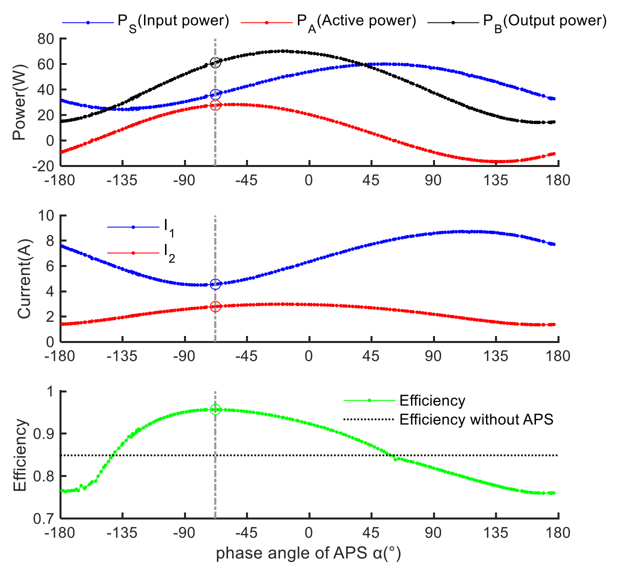

FIGURE 20. Experiment result of wireless charging system with the APS. The data of phase angle, current and power are all from the power analyzer PW6001. The definition of efficiency is related to the sign of active power, as described in (19) and (21). In the power figure, the output power is greater than the input power when $-152° < \alpha < 27°$ because the active power source is providing energy to the load.

However, it can be observed in this experiment that the efficiency improvement only occurs when the active power source provides energy to the outside. When the active power source works as a load, the current balance gets worse so the efficiency decreases accordingly.

V. CONCLUSION AND DISCUSSION

In this paper, a wireless charging system with active power source in receiver is proposed. The active power source is able to adjust its voltage and phase angle, and the efficiency can be improved in part of the operating range. A novel calculation method is used to obtain the efficiency of series-series compensation wireless charging circuit with active power source, and the results are verified by simulation. This paper explains that the efficiency improvement comes from two aspects: adjustment of power distribution and improvement of current balance. The efficiency improvement is demonstrated by an experimental system. The efficiency increases from 84.9% to 95.7% in a low coupling and slightly detuning condition.

Here are some discussions about the practical value of the active power source. As described in part I, the electric vehicle usually charges in a Constant Current - Constant Voltage (CC-CV) way. The voltage and the current varies significantly, and as a result, it is difficult for a unidirectional wireless charging system to meet charging requirement and achieve current balance simultaneously. The active power source provides a feasibility to adjust the power flow. It can work as a load at the earlier stage of charging, and work as a power source (or a negative load) at the later stage. In this way, it is possible to realize efficiency improvement and energy balance of active power source during the whole charging process.

However, there are some problems in practical use. First, extra energy loss will be generated during the charging-discharging operation of active power source, which will weaken the effectiveness of efficiency optimization. Moreover, a significant efficiency improvement requires an active power source with an energy level comparable to that of the vehicle battery, which may bring problems of vehicle economy and spatial arrangement. Follow-up researches can be carried out on this basis.

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