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A Novel Wireless Energy Router for Home Energy Management with Omnidirectional Power Transmission

Yuxin Liu, Chunhua Liu, Senior Member, IEEE, Zhiping Dong, Senyi Liu, and Wusen Wang

Abstract—Home energy management system (HEMS) dynamically regulates energy production and consumption to reduce energy usage costs and increase power efficiency. By combining wireless power transfer (WPT) technology with energy routers, this paper proposes a new wireless energy router system for HEMS to realize omnidirectional cableless energy interconnection among various energy storage devices, like portable electronics, electric vehicles, and energy storage stations. The proposed system contains an energy router and multiple transceivers. Each transceiver can be charged and discharged through two independent power channels with different operating frequencies. First, two orthogonal router coils with LCC compensations work at two operating frequencies, enabling omnidirectional power transmission with the transceiver coils. Accordingly, a dual-frequency constant-current compensation (DCC) network is proposed for the transceiver circuits to offer constant coil current operation. Furthermore, a decoupled phase-shift control with a power flow tracking algorithm is introduced to achieve independent power control for each transceiver. Finally, a parameter design procedure is developed, where a SIC-MOSFET prototype with three transceivers is used to verify the effectiveness of the proposed system. Experimental results prove that the transceivers can get energy interconnection from all directions, and the power flow can be regulated independently from the transceiver side.

Keywords—Wireless power transfer (WPT), wireless energy router, home energy management system, omnidirectional power, compensation network.

I. INTRODUCTION

As an indispensable link of the future smart grid, the home energy management system (HEMS) conveniently and intelligently coordinates the energy production and consumption of home appliances, electric vehicles, renewable energies, and energy storages [1-3]. HEMS has the potential to reduce electricity bills, increase energy efficiency, and promote renewable energies [3]. With multiple connection ports and flexibly handling power flows among sources and loads, the energy router becomes a suitable energy interface for HEMS [4, 5]. However, most existing energy routers use direct wires to connect each power unit and can only realize conductive power transmission. As a rapidly expanding technology with a great prospect, wireless power transfer (WPT) has been widely applied in various applications [6, 7], like wireless motors [8], portable electronics [9], medical implants [10], and electric vehicles (EVs) [11]. More and more devices with WPT functions are closely related to people's daily lives, bringing great convenience and safety, and the experience of using electrical energy has been significantly changed and improved [7-9]. Therefore, there is a growing demand for wireless energy routers (WERs) to provide cableless energy interconnection among various devices and meet the needs of future HEMS applications. However, several challenges remain in building such a WER for HEMS, including 1) it is difficult to provide stable power transmission due to the dramatical change of mutual inductance when the device position changes; 2) bidirectional power transmission demand for charging and discharging operations; 3) decoupled power regulation ability for all connected power devices.

Previous studies have explored the potential of WPT to incorporate more flexibility and freedom. In [12, 13], basic mathematical theories of free-positioning omnidirectional WPT are developed. In free-positioning omnidirectional WPT systems, the loads can receive sufficient power at any position around the transmitter [12-14]. Multiple orthogonal coils are applied on the transmitter side and are capable of generating a magnetic field in multiple directions, which provides a great tolerance for misalignment and angular deviation [15, 17]. In [16], an omnidirectional WPT with multiple loads is proposed. Multiple capacitors and switches are used in the transmitter circuit to generate various resonant frequencies, and selective power transmission can be achieved. In [18], a phase-shift control is proposed for a two-phase two-load WPT system. Two orthogonal coils work at different frequencies, and a target power distribution to loads with high misalignment can be realized. However, most existing omnidirectional WPT systems suffer from complicated control methods and only achieve one-way power transmission from the transmitters to the receivers, thus not offering more complicated power-sharing functions. Moreover, for multi-load omnidirectional WPT systems [16, 18], each transmitter coil needs to maintain sufficient mutual inductance with the receiving coils. Otherwise, the coil current will increase dramatically [19, 20].

When both the primary and the secondary converters are active, the bidirectional power flow is enabled in a WPT system [21-23]. In [22, 23], synchronization methods for phase-shift control are proposed to eliminate the influence of the communication delay and improve the reliability of bidirectional power regulation. In [24], a closed-loop controller is proposed to optimize the overall efficiency of the bidirectional-power WPT system, which dynamically calculates the most appropriate phase-shift angles with the circuit parameters. However, these bidirectional-power WPT systems can only handle power transmission between two power units but cannot achieve more complex energy...
interaction among multiple units. In [25], a wireless energy
trading system is developed for traffic internet, where the road
junctions and roadways are electrified as traffic energy routers.
This traffic energy router enables EVs to relay, upload or
download wireless energy packages. However, the traffic
energy router cannot realize the independent power control for
each EV, and a power change in one vehicle will affect other
vehicles. Moreover, when there is a load open circuit or a
decrease in mutual inductance, the coil current can increase
significantly, causing the burn-out of the transmitter coils [20].

In order to realize omnidirectional cableless energy
interconnection among various energy storage devices at home
and solve the limitations of the existing WER, a novel WER
for HEMS with omnidirectional power transmission is
proposed in this paper. The proposed WER aims to optimize
people's experience using electric power in home applications
[1-3]. The main contributions are listed as follows.
(a) The system includes an energy router and multiple
transceivers. The transceivers perform omnidirectional
wireless energy interconnection with the energy router
through independent power channels and realize
operations like charging, discharging, and energy sharing.
(b) A dual-frequency constant-current compensation (DCC)
network is proposed for the transceiver coils, and LCC
compensations are applied for the two orthogonal router
coils. Both the transceiver and router coils can achieve
constant current (CC) operation, which prevents the coils
from burn-out due to the coil current increase caused by
the change of mutual inductance.
(c) A decoupled phase-shift control with a power flow
tracking algorithm is proposed to achieve independent
power control for the transceivers. The power of each
transceiver can be regulated from the transceiver's side.
(d) A parameter design procedure is given in the form of a
flow chart, which reduces the cross-interference of the
two power channels.

II. SYSTEM CONFIGURATION AND MODEL

A. WER for Home Energy Management

Fig. 1 demonstrates the application of proposed
two-dimensional omnidirectional WER system for HEMS. The
router side contains two parts, Part A and Part B. Each part of the
circuit contains a full-bridge converter (\(S_{1x}, S_{2x}, S_{1h}, \text{and } S_{2h}\))
are the switching state of the power switches, \(x = a, b, 1\)
represents on, and 0 represents off.), an LCC compensation
network \((L_{px}, C_{px}, \text{and } C_{tx})\), and one of the orthogonal coils
\((L_{tx})\). \(U_{bus}, u_{px}, i_{px}, \text{and } i_{tx}\) are DC bus voltage, converter
output voltage, converter output current, and transmission coil
current, respectively. The transceiver side consists of \(n\)
independent units corresponding to \(n\) energy storage devices.
Each unit has a transceiver coil \((L_{kr}, k = 1, 2, ... , n)\), a dual-
frequency constant-current compensation (DCC) \((C_{rk}, C_{vk},
L_{vk}, L_{bk}, \text{and } C_{bk})\), a full-bridge converter \((S_{1rk}, S_{2rk}, S_{1bk}, \text{and }
S_{2bk})\), a DC capacitor \((C_{dcx})\), and a DC power source
\((U_{dck})\). \(u_{rk}, i_{rk}, \text{and } i_{rx}\) are converter output voltage,
converter output current, and receiver coil current.

![Fig. 1 Proposed omnidirectional WER for HEMS.](image1)

![Fig. 2 Circuit configuration of the proposed omnidirectional wireless energy router.](image2)

![Fig. 3 Equivalent circuit of the proposed WER.](image3)

As shown in Fig. 2, the two parts of the energy router side
operate at two different frequencies, \(f_a\) and \(f_b\). Accordingly,
the converter output voltages \(u_{tx}\) of the transceivers contain
the voltage components of \(f_a\) and \(f_b\). The first bridge arms of
the converters operate at the frequency of \(f_a\), while the second
bridge arms operate at the frequency of \(f_b\). \(u_{sk}\) can be expressed as:

\[
u_{sk} = u_{PDR} - u_{NOR} = U_{dck}(S_{1sk} + S_{2sk} - 1)
\]

where \(u_{PDR}\) is the output voltage of the first bridge arm, and
\(u_{NOR}\) is the output voltage of the second bridge arm. The DCC
network is based on T-type networks. Compared with the LCC
network, the DCC network uses one more inductor and one
more capacitor but can generate two operating frequencies with constant coil current output for the transceiver units. The DCC network can also be utilized in various one-to-many WPT systems [30] and many-to-one WPT systems.

Fig. 3 is the equivalent circuit of the proposed WER. \( M_{ab} \) and \( M_{bb} \) denote the mutual inductances between the router coils and the transceiver coils. Router coils are much larger than the transceiver coils, and the transceiver coils are far enough apart that their mutual inductance is negligible [26]. Moreover, the two router coils are orthogonal, and their mutual inductance can also be neglected. \( R_{tx} \) and \( R_{rk} \) are the resistances of the router coils and transceiver coils. For the T-type compensated WPT system, when the coil current mainly occurs at the fundamental frequency component, the energy is mainly transmitted in the form of the fundamental frequency. Therefore, the first harmonic approximate (FHA) method [32] is valid for analyzing the power flow of the system. Based on Fig. 3, the system can be modeled as:

\[
\begin{align*}
\mathbf{U}_{px} &= j\omega L_{px}\mathbf{I}_{px} + Z_{tx}\mathbf{I}_{tx} + j\omega \sum_{i=1}^{N} M_{2i}I_{tx}^i \\
0 &= -\frac{1}{j\omega C_{pk}} + (Z_{tx}^i + j\omega L_{tx})\mathbf{I}_{tx}^i + j\omega \sum_{i=1}^{N} M_{2i}I_{tx}^i \\
\mathbf{U}_{sk} &= Z_{sk}\mathbf{I}_{sk} + j\omega M_{at} \mathbf{I}_{tx} + j\omega M_{bt} \mathbf{I}_{tx} \\
0 &= -Z_{sk}^i \mathbf{I}_{sk}^i + (Z_{rk}^i + j\omega M_{ak} \mathbf{I}_{tx}^i + j\omega M_{bk} \mathbf{I}_{tx}^i)
\end{align*}
\]

(2)

\[\mathbf{I}_{tx} = \mathbf{I}_{tx}^i \]

\[\mathbf{I}_{sk} = \mathbf{I}_{sk}^i \]

\[Z_{tx}^i = \frac{1}{j\omega C_{pk}} + j\omega L_{tx} + \mathbf{R}_{tx} \]

\[Z_{rk}^i = \frac{1}{j\omega C_{pk}} + j\omega L_{rk} + \mathbf{R}_{rk} \]

\[Z_{sk}^i = \frac{1}{j\omega C_{pk}} + j\omega L_{sk} \]

(3)

\[u_{pa} \] does not contain the voltage component with a frequency of \( f_0 \), and \( u_{pb} \) does not contain the voltage component with a frequency of \( f_a \), expressed as:

\[u_{pa}^i = 0, u_{pb}^i = 0 \]

(4)

The two LCC compensation networks are tuned with operating frequencies \( f_a \) and \( f_b \), as:

\[\begin{align*}
\mathbf{I}_{pa} &= j/(\omega_a C_{pa}) = j/(\omega_a L_{ta} - 1/(\omega_a C_{ta})) \\
\mathbf{I}_{pb} &= j/(\omega_b C_{pb}) = j/(\omega_b L_{tb} - 1/(\omega_b C_{tb}))
\end{align*} \]

(5)

For the DCC compensation networks from the transceiver circuits, the parameters are tuned as:

\[\begin{align*}
L_{hk} &= L_{rk} + C_{sk} = C_{rk} \\
\omega_a^2 L_{zk} C_{sk} &= \omega_a^2 L_{zk} C_{sk} - 1 \omega_a^2 L_{zk} C_{sk} - 1 \omega_a^2 L_{zk} C_{sk} - 1
\end{align*} \]

(6)

Thus, the following relations can be found:

\[Z_{rk}^i - \mathbf{R}_{rk} = -Z_{sk}^i = Z_{hk} \]

(7)

Solving (2)-(7) yields:

\[i_{pk}^i = \frac{j\omega L_{px}^i \mathbf{I}_{px}^i}{\omega_a^2 Z_{tx}^i + j\omega L_{tx} + \sum_{i=1}^{N} M_{2i} \mathbf{I}_{tx}^i}(x = i) \]

\[i_{pk}^i = \frac{j\omega L_{px}^i \mathbf{I}_{px}^i}{\omega_a^2 Z_{tx}^i + j\omega L_{tx} + \sum_{i=1}^{N} M_{2i} \mathbf{I}_{tx}^i}(x = i) \]

(8a)

\[i_{pk}^i = \frac{j\omega L_{px}^i \mathbf{I}_{px}^i}{\omega_a^2 Z_{tx}^i + j\omega L_{tx} + \sum_{i=1}^{N} M_{2i} \mathbf{I}_{tx}^i}(x = i) \]

(8b)

\[i_{tx}^i = \frac{j\omega L_{tx}^i \mathbf{I}_{tx}^i}{\omega_a^2 Z_{tx}^i + j\omega L_{tx} + \sum_{i=1}^{N} M_{2i} \mathbf{I}_{tx}^i}(x = i) \]

(8c)

\[i_{tx}^i = \frac{j\omega L_{tx}^i \mathbf{I}_{tx}^i}{\omega_a^2 Z_{tx}^i + j\omega L_{tx} + \sum_{i=1}^{N} M_{2i} \mathbf{I}_{tx}^i}(x = i) \]

(8d)
The total output power of the Transceiver $k$ is:

$$P_{sk} = P^{(a)}_{sk} + P^{(b)}_{sk} \quad (16)$$

In (15), the signs of $\omega_a^2 C_{hk} L_{hk} - 1$ and $\omega_b^2 C_{hk} L_{hk} - 1$ are determined by the circuit parameters, and the signs of $M_{ak}$ and $M_{bk}$ are determined by the position of the transceiver coils. When $P^{(a)}_{sk} > 0$ and $P^{(b)}_{sk} > 0$, the $k$th transceiver discharges power to the router. Alternately, when $P^{(a)}_{sk} < 0$ and $P^{(b)}_{sk} < 0$, the router delivers power to the $k$th transceiver.

III. POWER FLOW CONTROL

A. Decoupled Phase-shift Control

Phase-shift control is usually employed in a bidirectional-power WPT system to achieve smooth power flow regulation capability [21-23]. A decoupled phase-shift control is developed for the proposed WER, and the control signals and converter output voltage are shown in Fig.4. For the full-bridge converters from the router side, $S_{1a}, S_{2a}, S_{1b},$ and $S_{2b}$ have constant 50% duty ratio. $S_{1a}$ and $S_{2a}$ have a frequency of $f_a$, and $\alpha_a$ is their phase difference. $S_{1b}$ and $S_{2b}$ have a frequency of $f_b$, and $\alpha_b$ is their phase difference. For the converter in Transceiver $k$, $S_{1k}$ and $S_{2k}$ have a frequency of $f_a$ with a variable duty ratio $\beta_{ak}$, and $S_{2k}$ have a frequency of $f_b$ with a variable duty ratio $\beta_{bk}$. $\theta_{ak}$ is the phase difference between the rising edges of $S_{1a}$ and $S_{1k}$. $\theta_{bk}$ is the phase difference between the rising edges of $S_{2a}$ and $S_{2k}$. Then, $\theta_{ak}$ and $\theta_{bk}$ can be calculated as:

$$\begin{align*}
\theta_{ak} & = \theta_{ak} + \frac{\pi}{2} (\beta_{ak} - \alpha_a) \\
\theta_{bk} & = \theta_{bk} + \frac{\pi}{2} (\beta_{bk} - \alpha_b)
\end{align*} \quad (17)$$

The amplitudes of converter output voltages are given as:

$$\begin{align*}
U_{mpa} &= \frac{4}{\pi} U_{bus} \sin \frac{\alpha_a}{2} \\
U_{mpb} &= \frac{4}{\pi} U_{bus} \sin \frac{\alpha_b}{2} \\
U_{mask} &= \frac{2}{\pi} U_{dck} \sin \frac{\beta_{ak}}{2} \\
U_{msbk} &= \frac{2}{\pi} U_{dck} \sin \frac{\beta_{bk}}{2}
\end{align*} \quad (18)$$

(12)-(18) indicate that when the signs of $M_{ak}, M_{bk}, \omega_a^2 C_{hk} L_{hk} - 1$, and $\omega_b^2 C_{hk} L_{hk} - 1$ are settled, the power flow of Transceiver $k$ can be controlled by adjusting $\gamma_{ak}, \gamma_{bk}, \beta_{ak}, \beta_{bk}, \alpha_a, \alpha_b$. Particularly, when $\gamma_{ak} (\gamma_{bk})$ equals to $\pi/2$ or $3\pi/2$, no reactive power is involved in power exchanging [23, 24]. To reduce the additional power loss caused by reactive power, $\gamma_{ak}$ and $\gamma_{bk}$ should be:

$$\gamma_{ak}, \gamma_{bk} \in \left[\frac{\pi}{2}, \frac{3\pi}{2}\right] \quad (19)$$

Moreover, once $\alpha_a$ and $\alpha_b$ change, the power flow of all transceivers will change. To enable independent power regulation on the transceiver side for each transceiver, $\alpha_a$ and $\alpha_b$ are set to constant values. In this case, the magnitude of the power flow is subject to $\beta_{ak}$ and $\beta_{bk}$, and direction of the power flow is subject to $\gamma_{ak}$ and $\gamma_{bk}$. The decoupled power flow control of each transceiver can be achieved.

B. Power Flow Tracking Method

In the real application of the WER, the mutual inductance $(M_{ak}$ and $M_{bk}$) can change with the position of the receiver. Fig. 5 (a) displays the top view of the two router coils ($L_{ta}$ and $L_{tb}$) and one transceiver coils ($L_{rk}$), where $\theta_{pk}$ denotes the relative rotation angle of the transceiver coil. The influence of $\theta_{pk}$ on $M_{ak}$ and $M_{bk}$ is simulated using finite-element analysis (FEA), and the simulation results are shown in Fig. 5 (b). Fig. 5 (b) indicates changes in $\theta_{pk}$ can affect the magnitude and the signs of $M_{ak}$ and $M_{bk}$, which further affects the power flow. Therefore, the power flow tracking method is proposed to prevent deviations in the magnitude and direction of the transmitted power.

The flow chart of the proposed power flow tracking method is shown in Fig. 6, which is mainly composed of the power direction tracking part and power magnitude tracking part. The proposed control method can correct the power flow direction after start-up and coil position movement. And then dynamically adjust the power amplitude so that the actual power follows the reference value. At the beginning, the reference power $P_{refk}$ is given, and the variables are set to the initial values as: $\gamma_{ak} = \pi/2$, $\gamma_{bk} = \pi/2$, $\beta_{ak} = 0$, and $\beta_{bk} = 0$. Then, in the power direction tracking part, the power directions of the two channels are tested and adjusted separately with $\beta_{ak} = \beta_{test}$, $\beta_{bk} = 0$, or $\beta_{ak} = 0$, $\beta_{bk} = \beta_{test}$. $\beta_{test}$ is duty ratio of $S_{1k}$ or $S_{2k}$ when testing power direction. If the sign of the DC-side sampled power ($P_{sk}$) is different from the sign of the reference power $\gamma_{ak}$ and $\gamma_{bk}$ will be accordingly set to the alternate value ($3\pi/2$). Next, in the power magnitude tracking part, if the absolute value of $P_{refk}$ is higher than the absolute value of $P_{sk}$, $\beta_{ak}$ and $\beta_{bk}$ will increase, otherwise, $\beta_{ak}$ and $\beta_{bk}$ will decrease. In this case, $\beta_{ak}$ and $\beta_{bk}$ have the same value as:

$$\beta_{ak} = \beta_{bk} = \beta_k \quad (20)$$
The proposed control method is effective in tracking the reference power from the transceiver side. Further, the total power is automatically distributed to the two power channels depending on the value of $M_{sk}$ and $M_{bh}$. Moreover, since both the router coils and transceiver coils can achieve CC operation, when the mutual inductance becomes small, the inverter output current will not increase significantly, thus avoiding the burn-out of the coils.

![Flow chart of the parameters design procedure](image)

**IV. PARAMETER DESIGN**

The parameter design is closely related to the performance of a WPT system [6, 7]. It is necessary to develop the parameter design scheme of the designed WER system. Initially, the operating frequencies ($f_a$, $f_b$) are commonly chosen based on various requirements or standards [26]. The converter output voltage of the transceiver ($u_{sk}$) is the superpositions of two waveforms, $u_{sk}^{(a)}$ and $u_{sk}^{(b)}$. $u_{sk}^{(a)}$ has the fundamental frequency of $f_a$, and $u_{sk}^{(b)}$ has the fundamental frequency of $f_b$. Then, the Fourier decomposition of $u_{sk}$ can be expressed as:

$$u_{sk}^{(a)} = \frac{2}{\pi} u_{dc} + \frac{2}{\pi} \sum_{n=1}^{\infty} \sin \left(\frac{2\pi n}{z} t\right) \cos \left(n \omega_a t + \phi_a\right)$$

$$u_{sk}^{(b)} = \frac{2}{\pi} u_{dc} + \frac{2}{\pi} \sum_{n=1}^{\infty} \sin \left(\frac{2\pi n}{z} t\right) \cos \left(n \omega_b t + \phi_b\right)$$

where $\phi_a$ and $\phi_b$ are the initial phase angle of $u_{sk}^{(a)}$ and $u_{sk}^{(b)}$.

(21)-(23) indicate $u_{sk}^{(a)}$ and $u_{sk}^{(b)}$ contain both odd and even harmonics. If $u_{sk}^{(a)}$ and $u_{sk}^{(b)}$ have overlap in the frequency spectrum, the decoupling of the power flow control of the two channels will be affected. Therefore, it should be avoided to set $f_a$ ($f_b$) as an integral multiple of $f_b$ ($f_a$).

Then, the inductance of transmitter and receiver coils are obtained by winding wires [26], and $L_{tx}$ and $L_{rx}$ are settled.

Next, the parameters for the LCC compensations from the router circuit are decided. When considering the effects of the cross-interference currents ($I_{pa}^{(b)}$, $I_{pa}^{(a)}$, $I_{pb}^{(b)}$, and $I_{pb}^{(a)}$), the active output power of the router ($P_{pa,f}$ and $P_{pb,f}$) is calculated as:

$$P_{pa,f} = \frac{1}{2} \text{Re} \left\{ \left( U_{pa}^{(a)} \right)^* \cdot \left( I_{pa}^{(a)} \right)^* + U_{pa}^{(b)} \cdot \left( I_{pa}^{(b)} \right)^* \right\} = P_{pa}$$

$$P_{pb,f} = \frac{1}{2} \text{Re} \left\{ \left( U_{pb}^{(a)} \right)^* \cdot \left( I_{pb}^{(a)} \right)^* + U_{pb}^{(b)} \cdot \left( I_{pb}^{(b)} \right)^* \right\} = P_{pb}$$

And the output power of the receivers ($P_{sk,f}$) can be expressed in (25), shown at the bottom of this page. In (24) and (25), $P_{pa}$, $P_{pb}$, $I_{sk}^{(a)}$, and $P_{sk}^{(b)}$ are values of output power without considering the cross-interference currents, calculated in (12) and (15). (24) and (25) indicate that the cross-interference currents have no influence on the output power of the energy router but can affect the output power of the transceivers. In (25), the expressions of $P_{sk,f}^{(a)}$ and $P_{sk,f}^{(b)}$ respectively contain $U_{sl}^{(a)}$ ($l = 1, 2, ..., n$) and $U_{sl}^{(b)}$. The Part A of the router works as a relay to exchange power with a frequency of $f_b$, and the Part B of the router works as a relay to exchange power with a frequency of $f_a$. (25) shows that when the output voltage of one transceiver changes, the output power of the other transceivers will also change. It affects the independent power regulation ability of each transceiver. Therefore, the effects of the cross-interference currents should be minimized during the design of the circuit parameters. The cross-interference can be reduced by increasing the network impedance at the unwanted frequencies [30, 31]. According to (8) and (25), the effect of the cross-interference currents can be reduced by increasing the impedance of Part B at a frequency of $f_a$ and the impedance of Part A at a frequency of $f_b$, expressed as:

$$\left| \frac{1}{\omega_a^2 \omega_b^2 (1-\omega_a^2 \omega_b^2 g_{pa})} \right| \geq Z_{f,a}$$

$$\left| \frac{1}{\omega_a^2 \omega_b^2 (1-\omega_a^2 \omega_b^2 g_{pb})} \right| \geq Z_{f,b}$$

where $Z_{f,a}$ denotes the minimum value preset for impedances of Part A and Part B. The larger $Z_{f,a}$, the less the influence of the cross-interference currents. Boundaries are preset for $L_{pa}$, $C_{ux}$, and $C_{tx}$. Various combinations of $L_{pa}$ and $L_{pb}$ are tried out to calculate $C_{ux}$ and $C_{tx}$ by (5). $L_{pa}$, $C_{ux}$, and $C_{tx}$ should meet the requirement of (26) and the limitations of the boundaries. For the calculation of the DCC compensation of the received, $C_{ux}$, $C_{tx}$, $L_{ux}$, $L_{tx}$, and $C_{tx}$ can be calculated based on (6). Also, the obtained parameters should meet the preset boundaries. Accordingly, a parameter design procedure is proposed in a flow chart for the WER, as shown in Fig. 7.

Based on the parameter design procedure, a WER with three transceivers is designed, and the parameters are listed in TABLE I. The interaction between routers and transceivers can be represented by reflected impedances in series with coils [7]. When $U_{mpa} = U_{mpb} = 100V$, and $U_{mst} = 60V$, Fig. 8 (a), (b), and (c) respectively show the frequency sweeping results of $i_{tx}$, $i_{rb}$, and $i_{tx}$ under various reflected impedances ($Z_{refa}$, $Z_{refb}$, and $Z_{refc}$). Fig. 8 indicates Part A and Part B of the router can achieve constant coil current at 100kHz and 150kHz, respectively. Moreover, the receivers can achieve constant coil current at both 100kHz and 150kHz, consistent with the analysis in Section II.
TABLE I. PARAMETERS FOR VERIFICATION

<table>
<thead>
<tr>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil inductance ($L_{p1}, L_{p2}, L_{p3}, L_{c1}, L_{c2}, L_{c3}$)</td>
<td>188.9, 199.1, 29.3, 30.2, 29.8μH</td>
</tr>
<tr>
<td>Coil resistance ($R_{p1}, R_{p2}, R_{p3}, R_{c1}, R_{c2}, R_{c3}$)</td>
<td>0.15, 0.16, 0.07, 0.07, 0.07Ω</td>
</tr>
<tr>
<td>LCC compensation ($L_{c1}, C_{c1}, C_{c2}, C_{c3}$)</td>
<td>14.4μH, 175.90, 14.52nF</td>
</tr>
<tr>
<td>LCC compensation ($L_{p1}, C_{p1}, C_{p2}$)</td>
<td>8.1μH, 139.01, 0.15nF</td>
</tr>
<tr>
<td>Equivalent resistances of $L_{p1}$ and $L_{p2}$</td>
<td>0.03, 0.02Ω</td>
</tr>
<tr>
<td>DC compensation of Transceiver 1 ($C_{p1}, C_{c1}, L_{c1}, L_{c2}, L_{c3}$)</td>
<td>56.30, 337.78, 56.29nF, 5.0, 29.8μH</td>
</tr>
<tr>
<td>DC compensation of Transceiver 2 ($C_{p2}, C_{c2}, L_{c2}, L_{c3}, L_{c4}$)</td>
<td>56.28, 337.80, 56.24nF, 5.1, 30.1μH</td>
</tr>
<tr>
<td>DC compensation of Transceiver 3 ($C_{p3}, C_{c3}, L_{c3}, L_{c4}, L_{c5}$)</td>
<td>56.27, 337.72, 56.25nF, 5.0, 30.2μH</td>
</tr>
<tr>
<td>Equivalent resistances of $L_{c1}, L_{c2}, L_{c3}$</td>
<td>0.01, 0.03, 0.00, 0.03, 0.01, 0.03Ω</td>
</tr>
<tr>
<td>DC voltage ($U_{outp1}, U_{dc1}, U_{dc2}, U_{dc3}$)</td>
<td>100, 60, 60, 60V</td>
</tr>
<tr>
<td>Operating frequency ($f_{op}$)</td>
<td>100, 150kHz</td>
</tr>
</tbody>
</table>

![Fig. 8 Frequency sweeping results of the coil currents under various reflected impedances. (a) Coil current of Part A. (b) Coil current of Part B. (c) Coil current of Receiver 1.](image)

![Fig. 9 Experimental prototype for the proposed system. (a) Setup of the prototype. (b) Coil configuration and size.](image)

V. EXPERIMENTAL VERIFICATION

A three-transceiver experimental prototype is built up to verify the proposed system's effectiveness, as shown in Fig. 9 (a). The parameters of the prototype are listed in TABLE I. The configurations and size of the coils are shown in Fig. 9 (b). SIC-MOSFETs (C3M000606SK) from CREE are power switches of each full-bridge converter. The oscilloscope (MSO46), current probe (TCP A300), and voltage probe (P5200A) are all from TEKTRONIX. The LCR meter (E4980AL) from KEYSIGHT is used to measure the system parameters. TMS320F28379D from TI and XC6LX25 from XILINX are applied in the controller.

As shown in Fig. 10, the prototype operates in three modes to demonstrate the flexibility of the proposed system in handling the power flow, namely, charging mode, discharging mode, and energy sharing mode. All the three operating modes are tested with the router-side internal phase-shift angles of $\alpha_a = 21\pi/25$ and $\alpha_b = 18\pi/25$. The transceiver coils are set to different positions around the router coils with 350mm center-to-center coil distance, which verifies an omnidirectional power interaction can be achieved between the energy router and the three transceivers.

Fig. 10 (a) shows the experimental results of the charging mode, where the positions of the transceiver coils are $\theta_{p1} = 0^\circ$, $\theta_{p2} = 45^\circ$, and $\theta_{p3} = 270^\circ$. In the charging mode, the energy router delivers positive real power to the three transceivers. With the proposed power flow tracking method in Section III, the values of reference power are set for each transceiver as $P_{ref1} = -60W$, $P_{ref2} = -40W$, and $P_{ref3} = -70W$. The actual measured output power of the receivers and the energy router from the DC side are $P_{r1} = -60.78W$, $P_{r2} = -40.80W$, $P_{r3} = -70.26W$, and $P_p = 222.30W$. In this case, the overall DC-to-DC efficiency [8] is 77.30%. For the transceivers, the waveforms of converter output voltages and coil currents ($u_{sk}$ and $i_{sk}$) contains the components of frequencies of 100kHz and 150kHz. Under the power flow tracking method, the relative phase-shift angles maintain stable as $\gamma_{a1} = 3\pi/2$, $\gamma_{a2} = \pi/2$, $\gamma_{a3} = 3\pi/2$, and $\gamma_{b3} = \pi/2$. This indicates the proposed control method can track the direction of the power flow by $\gamma_{sk}$ and $\gamma_{bk}$, and track the magnitude of the power flow by $\beta_k$. 

Fig. 10 (b) shows the experimental results of the discharging mode with $\theta_{p1} = 315^\circ$, $\theta_{p2} = 45^\circ$, and $\theta_{p3} = 225^\circ$. In the discharging mode, the three transceivers feedback positive real power to the energy router. The reference powers for the transceivers are set as $P_{ref1} = 80W$, $P_{ref2} = 50W$, and $P_{ref3} = 80W$. In this case, the actual measured output power of the receivers and the energy router from the DC side are $P_{r1} = 80.54W$, $P_{r2} = 50.48W$, $P_{r3} = 80.66W$, and $P_p = -167.46W$. And the overall DC-to-DC efficiency of the system is 79.11%. With the proposed power flow tracking method, the value of the relative phase-shift angles are $\gamma_{a1} = \pi/2$, $\gamma_{b1} = 3\pi/2$, $\gamma_{a2} = 3\pi/2$, $\gamma_{b2} = 3\pi/2$, $\gamma_{a3} = \pi/2$, and $\gamma_{b3} = \pi/2$.

Fig. 10 (c) shows the experimental results of the energy sharing mode when the relative rotation angles of the receiver coils are $\theta_{p1} = 45^\circ$, $\theta_{p2} = 135^\circ$, and $\theta_{p3} = 315^\circ$. In the energy sharing mode, some receivers transmit energy to the other receivers through the energy router. The energy router acts as a relay to build energy channels for the transmitters and the receivers, and the DC-side output power of the router is zero. In this demonstration, the reference powers for the transceivers are set as $P_{ref1} = -90W$, $P_{ref2} = 70W$, and $P_{ref3} = 46W$. In this case, the actual measured output power of the receivers and the energy router from the DC side are $P_{r1} = -89.37W$, $P_{r2} = 70.76W$, $P_{r3} = 46.69W$, and $P_p = -0.56W$. Transceiver 2 and Transceiver 3 transmit energy to Transceiver 1, and the overall DC-to-DC efficiency of the system is 76.09%. With the proposed power flow tracking method, the values of the relative phase-shift angles are stable as $\gamma_{a1} = \pi/2$, $\gamma_{b1} = \pi/2$, $\gamma_{a2} = 3\pi/2$, $\gamma_{b2} = \pi/2$, $\gamma_{a3} = \pi/2$, and $\gamma_{b3} = 3\pi/2$.

Fig. 10 indicates the coil currents $i_{tx}$ and $i_{sk}$ can be controlled by the converter output voltage $u_{px}$ and $u_{sk}$, respectively. Moreover, when the mutual inductances $M_{sk}$ and $M_{bk}$ change, $i_{tx}$ and $i_{sk}$ do not change significantly, which is...
consistent with the analysis Section II. Thus, when the positions of the transceiver coils change, \(i_{tx}\) and \(i_{sk}\) will not increase significantly due to the reduction of mutual inductance, thus avoiding the burn-out of the coils.

Fig. 11 shows how the proposed control method tracks the reference power during start-up. The whole process contains two parts, namely power direction tracking and power magnitude tracking. For power direction tracking, two power channels of a transceiver are activated in turns and the values of \(\gamma_{ak}\) and \(\gamma_{bk}\) are adjusted according to measured power direction. Once \(\gamma_{ak}\) and \(\gamma_{bk}\) are decided, the control system will track the power magnitude. This increases \(\beta_{ak}\) and \(\beta_{bk}\) until the measured power magnitude reaches the reference value. Fig. 11 denotes the process of power direction tracking, and power magnitude tracking lasts about 30ms and 215ms.

Finally, the tested transceiver can receive 80W power from the energy router as the reference.

To further demonstrate the omnidirectional power interaction ability, a transceiver coil is placed at a variable relative rotation angle and center-to-center coil distances (250-450mm). The reference power is set to \(P_{ref1} = -80W\). The 3D polar plots of the actual measured power from the DC-side and the DC-to-DC efficiency are displayed in Fig. 12 (a) and (b), respectively. Fig. 12 indicates the transceiver can track reference power at any tested relative angles and coil distances.

The tested efficiency with one transceiver is 65.9% to 83.7%, depending on the values of the rotation angle and coil distance.

Moreover, a comparison is conducted between the simulated and calculated results, as shown in Fig. 13. In Fig. 13, the transparent surfaces are the calculated power of the two power channels of the router (\(|P_{pa}|\) and \(|P_{pb}|\)), while the solid surfaces denote the experimental results. For \(P_{pa}\) and \(P_{pb}\), their values are distributed according to the mutual inductance as analyzed in Section III. The variation trend of the experimental results and the calculated results are highly consistent, which verifies the power model and the effectiveness of the power flow tracking algorithm. The experimental surfaces are higher than the simulated surfaces due to various system losses. The system losses can vary with the change of coil position [27]. However, with the proposed closed-loop power tracking method, the power flow can still be regulated according to the reference value.

When the transceiver coil is not fully perpendicular, an angle offset can occur. Fig. 14 (a) depicts the coil configuration under angle offset, where \(\theta_{off}\) represents the transceiver coil offset angle from Z-axis, and \(D_{cb}\) denotes the distance from the coil bottoms. When \(D_{cb} = 300mm\) and \(P_{ref1} = -80W\), the power (\(|P_{sk}|\)) and efficiency (\(\eta\)) curves under various \(\theta_{off}\) are shown in Fig. 14 (b). Fig. 14 (b) indicates the system functions normally under tested offset.
angle (from 0° to 40°). However, since the mutual inductance decreases with the angle offset, the efficiency of the system decreases accordingly.

More experimental results with multiple transceivers under reference power change are presented in Table II. Three transceivers are placed in fixed locations. First, when the reference power values of the three transceivers are all set to 80W, which means all transceivers feedback power to the router. In this case, the overall DC-to-DC efficiency is 82.5%. Next, when the reference power of one or more of the transceivers drops, the measured efficiency drops accordingly. And the more power is dropped, the more severe the drop in efficiency. In all tested cases, the transceiver power can track the reference value.

Next, the power loss distribution [30] for the prototype is calculated, as shown in Fig. 15. In the power loss test, a transceiver coil is placed with 45° relative angle and 300mm center-to-center coil distance. The reference power is set to \( P_{\text{ref}} = -80W \). In Fig. 15, \( P_{\text{conv-\(LCC\)}} \), \( P_{\text{com-\(r\)}} \), \( P_{\text{com-\(t\)}} \), \( P_{\text{comp-\(r\)}} \), \( P_{\text{comp-\(t\)}} \), \( P_{\text{coil-\(r\)}} \), \( P_{\text{coil-\(t\)}} \), and \( P_{\text{other}} \) denote the router converter loss, transceiver converter loss, router compensation network loss, transceiver compensation network loss, router coil loss, transceiver coil loss, and other loss. Fig. 15 indicates the losses from compensation networks and coils account for a large proportion of the system losses. Therefore, the fabrication of compensation networks and coils is essential in improving system efficiency.

Table III gives a comparison of the recent works on omnidirectional WPT systems with various coil sizes and transmission distances. Compared with other omnidirectional WPT systems, the proposed WER can realize independent bidirectional-power regulation with multiple transceivers and reaches a relatively high transmission efficiency.

VI. CONCLUSION

In this article, a brand-new WER system for HEMS is proposed and implemented, which realizes omnidirectional cableless energy interconnection among various energy storage devices. In particular, two independent power channels with different operating frequencies are built for each...
transceiver to link the two orthogonal router coils. Besides, since the DCC network is proposed on the transceiver side and the LCC network is adopted on the router side, all coils can achieve constant coil current operation. Moreover, a decoupled phase-shift control with a power flow tracking algorithm is introduced to achieve decoupled power control for each transceiver. Finally, based on the parameter design procedure, a three-transceiver SIC experimental prototype is constructed to validate the feasibility of the proposed WER system. Experimental results indicate all the transceivers can realize operations such as charging, discharging, and energy sharing. Compared with the existing WER, the proposed system can realize stable omnidirectional power transmission and independent power regulation from the transceiver side.

APPENDIX

The system can be modified to a three-dimensional configuration to achieve a higher spatial misalignment level, as shown in Fig. 16. The router side contains three orthogonal coils, and LCC networks compensate them for obtaining constant coil current operation. The three networks are excited by converters with three different operating frequencies (ω₁, ω₂, and ω₃). For the transceiver part, converters with multi-frequency superposition are needed to generate the voltage waveforms with components with the frequencies of ω₁, ω₂, and ω₃. From the literature, two simple ways can be used to generate such excitation voltage. One way is to use the hybrid SPWM control method, which uses a high-frequency pulse to modulate components with different frequencies, as proposed in [31]. The second way is using the multi-level converters where the voltage steps walk at different operating frequencies, as proposed in [30]. In addition to the converter, the compensation network also needs to be modified. Constant coil current under three frequencies should be offered by the compensation network to avoid the burn-out of the coils under large variation of the mutual inductance. Fig. 17 (a) illustrates a practical solution for the three-frequency constant-current network.

Like the DCC network in Fig. 2, the three-frequency constant-current network is a T-type circuit with three branches. For the three-frequency constant-current network, the following relations should be ensured.

\[ L_h = L_t, C_{h1} = C_{t1}, L_{h1} = L_{t1} \]  (27)

And the following equation can be obtained.

\[ Z_h(\omega) = Z_t(\omega) + j\omega L_t \]  (28)

where \( Z_h(\omega) \) and \( Z_t(\omega) \) are expressed as

\[ Z_h(\omega) = j \frac{\omega L_h + \omega L_h (1 - \omega^2 L_h C_{h1})}{1 - \omega^2 L_h C_{h1}} \]  (29)

\[ Z_t(\omega) = j \frac{\omega L_t + \omega L_t (1 - \omega^2 L_t C_{t1})}{1 - \omega^2 L_t C_{t1}} \]  (30)

Also, the impedance of the vertical branch (\( C_v, C_{v1} \), and \( L_v1 \)) can be expressed as:

\[ Z_v(\omega) = j \frac{\omega L_v + \omega^2 L_v C_{v1} - 1}{\omega L_v (1 - \omega^2 L_v C_{v1})} \]  (31)

From (29), \( Z_h(\omega) \) at most have one positive real pole (\( \omega_{ph} \)) and one positive real zero (\( \omega_{zh} \)), and \( 0 < \omega_{ph} < \omega_{zh} \). Similarly, from (31), \( Z_v(\omega) \) at most have one positive real zero (\( \omega_{zh} \)), and one positive real pole (\( \omega_{ph} \)), and \( 0 < \omega_{zh} < \omega_{ph} \). Therefore, by configuring the parameters as \( \omega_{ph} < \omega_{zh} \) and \( \omega_{zh} < \omega_{ph} \), at least three frequencies (\( \omega_1, \omega_2, \) and \( \omega_3 \)) can be found that fulfill \( Z_h(\omega) = Z_v(\omega) \). The relation of impedance is shown in Fig. 17 (b). In the case of reflected impedance of \( Z_{ref}^{(i)} \) represents the three operating frequencies [30], \( i = 1, 2, 3 \) and input voltage \( U_{ref}^{(i)} \), the coil current \( I_{ref}^{(i)} \) can be expressed:

\[ I_{ref}^{(i)} = \frac{U_{ref}^{(i)} Z_{ref}^{(i)}}{Z_{ref}^{(i)} + Z_{ref}^{(i)} + Z_{ref}^{(i)} + Z_{ref}^{(i)}} \]  (32)

Equation (32) indicates the circuit can achieve constant coil current at three operating frequencies (\( \omega_1, \omega_2, \) and \( \omega_3 \)), proving the effectiveness of the three-dimensional configuration of the proposed WER. By using the three-dimensional configuration, a higher level of spatial misalignment can be achieved.

REFERENCES


