An Embedded Communication Method for In-Home Energy Routers With Power/Signal Dual Modulation

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Abstract—This article proposes a novel embedded communication strategy for in-home energy routers (IHERs). It is based on the power/signal dual modulation (PSDM) principle and applied in the small-scale community energy local area network (E-LAN). The proposed communication strategy multiplexes power converters as data transmitters, and thus high cooperation and synchronization between power flow and information flow are achieved. In addition, system reliability is enhanced since communication module has practically the same reliability as the power module. A typical IHER’s structure and operation principles are presented, based on which the detailed design of embedded communication is proposed. For distributed power management of community E-LAN, both intra-IHER communication and inter-IHERs communication are involved, and their channels are modeled mathematically. IHER interconnection interface converters (IICs) play a significant role in power exchange between IHERs, and their operation modes are analyzed in detail. Finally, an experimental prototype is built to validate the feasibility of the proposed method.

Index Terms—Embedded communication, energy local area network (E-LAN), in-home energy router (IHER), power/signal dual modulation (PSDM).

I. INTRODUCTION

THE need to diversify away from fossil fuel generation due to concerns over energy security, fuel price volatility, and the climate challenge is driving the deployment of nonconventional renewable energy (wind, small hydro, solar, tidal, geothermal, and in some cases waste) [1]. Because of their distributed, intermittent, and fluctuated characteristics, energy management is considered a key paradigm for the realization of complex energy systems [2]–[4], and distributed power management and flexible bidirectional power flow control are required. The energy Internet (EI) concept has been proposed [5]–[7] as a feasible solution, which deeply integrates energy technology and information technology, presenting a green vision of evolution [8]–[10].

Currently, EI has received extensive attention and several structures have been proposed [11]. Generally, there are three mainstream structures, which are bus structure, tree structure, and mesh structure [12]. Bus structure has great advantages of extension, but the common bus encounters congestion challenges in condition of large-scaled power and information interaction. Tree structure can efficiently isolate faults; however, it faces the bottleneck of efficient power control and management in promotion. Mesh structure does not need a central controller and gives more autonomy to energy entities, achieving better robustness and fault tolerance [13].

It requires high cooperation and synchronization between the power module and the communication module to guarantee distributed, reliable, and flexible power management, and it is usually applied in small-scale energy local area network (E-LAN), such as a residential community energy network.

In a community E-LAN, the in-home energy router (IHER) plays a significant role as the key element, interconnection equipment, and power management units [14] for each house. Meshed connections require proper energy routing to achieve efficient and intelligent distributed power management, for which real-time and reliable communication between IHERs are indispensable. Conventional communication approaches mainly include wireless communication, fieldbus, and Ethernet. Wireless communication technology is commonly used, which mainly includes ZigBee, Bluetooth, and Wi-Fi [15]. It has the advantages of low cost and simple structure, but
encounters security and reliability problems. For example, off-the-shelf wireless communication solution IEEE 802.11 Wi-Fi standard is vulnerable to denial-of-service (DoS) attack, which can be easily conducted through jamming [16]. In addition, if the Wi-Fi access point is deployed in the same area, it may corrupt ZigBee packet and cause severe interference [17]. Fieldbus has the advantages of high reliability with mature protocols, but numerous interface protocols reduce the design compatibility. Ethernet supports faster communication rate and more complex communication protocols, but is unsatisfactory in real-time performance. In addition, both the fieldbus and Ethernet require extra communication wires and data transmitters, which increase the system cost and complexity, as well as the risk of system failures.

To solve the abovementioned problems, power line communication (PLC) technology has been developed to enhance the integration of power and information for the purpose of better system reliability, lower cost, and simpler structure [18], [19]. In [20], a power packet router is designed and validated experimentally in a distributed network. Flexible power exchange between routers is achieved, and information tag is attached to the power packet. However, frequent power jumps deteriorate the system’s stability and reliability. In [21], a novel PLC technique is proposed, in which digital data are integrated into every power packet as the header and the footer. It may have admired performance in low voltage (e.g., 24, 48 V) applications, but does not adapt to high voltage (e.g., 220, 400 V) applications because of much power consumptions and reliability problem. Therefore, the existing PLC strategies cannot well satisfy the requirement of EI applications, which includes high cooperation and synchronization between power and information, as well as the requirement in security, simplicity, and reliability.

To overcome the above-mentioned weaknesses of PCL technology, some researchers have proposed to multiplex power converters as data transmitters. He et al. [22] reveal the info nature of power converters and propose a power and data dual modulation strategy, which is a novel perspective to study power converter embedded communications. However, it mainly focuses on the general theories and principles, but lacks targeted design analysis for energy router applications. According to the info nature of power converters, Wang et al. [23], Du et al. [24], and Wu et al. [25] propose switching ripple communication strategies based on Buck/Boost converters and phase shift full bridge converters, respectively. Inherent switching ripples of power converters are utilized as data carrier, but the amplitude cannot be flexibly controlled. Angjelicinoski et al. [26] propose a control loop modulation strategy named “power talk” based on power converters. Baseband data transmission is adopted, and thus the communication rate is significantly low (0.001–100 bps) [27]. As a result, it is more suitable to be used as a complementary strategy to wireless communication [28]. Zhu et al. [29] propose an embedded PLC based on a photovoltaic (PV) optimizer. Digital data are modulated to the carrier in the control loop and 2-kbps communication is achieved. However, it is designed for series connected PV optimizers only, and is not applicable in energy routers.

This article makes full use of the info nature of power converters and proposes an embedded communication strategy based on the power/signal dual modulation (PSDM) principle for IHER applications. High cooperation and synchronization of power flow and information flow are achieved, providing the backbone of distributed community E-LAN power management. As the key component in the IHERs, interconnection interface converters (ICs) are focused on, based on which communication channel model is constructed and operation modes are analyzed. The IHER prototypes are built and the proposed communication strategy is experimentally validated. The main contributions of this article are summarized as follows:

1) This article presents the basic principle of PSDM from both power electronics and information theory perspectives, and provides some implementation guidelines of PSDM in IHER.
2) Two types of IICs are presented for galvanic isolated and nonisolated conditions, respectively, and their four operation modes are analyzed.
3) Comprehensive experimental results are provided to verify the feasibility of the proposed PSDM-based IHER, e.g., four operation modes with both Buck/Boost IIC and dual active bridge (DAB) IIC, bit error rate (BER) test with 100-m transmission distances, etc.

This article is arranged as follows: Section II provides the general structure and operation principle of the IHER. Section III presents the principle and design details of PSDM method for IHER application, including intra-IHER communication design and inter-IHERs communication design. In Section IV, experimental validation is given based on a prototype system. Finally, a conclusion is drawn in Section V.

II. GENERAL STRUCTURE OF ENERGY ROUTERS AND OPERATION PRINCIPLE OF IICs

Fig. 1(a) shows a typical structure of an IHER, which includes three modules: power module, communication module, and control module. The power module is composed of a common dc power bus and several interface converters (ICs) connected in parallel. In this article, a 370-V dc power bus is adopted, and the ICs are divided into three categories: 1) dc 48-V ICs, which are compatible with an LED lighting system and chargers for consumer electronics; 2) dc 400-V ICs, which are compatible with PV power generations and electric vehicle chargers; and 3) ac 220-V ICs, which are compatible with the main grid and some household appliances, like washing machines and refrigerators. To enhance the universality, all ICs are designed to be bidirectional, and bridge topologies are employed for the convenience of IC reconstruction and multiplexing in future research. Therefore, two-stage Buck/Boost converters are adopted as dc 48-V ICs; Buck/Boost converters are adopted as dc 400-V ICs; full bridge converters are adopted as ac 220-V ICs. The control module is composed of several controllers corresponding to each IC. The communication module is composed of data transmitters and communication wires, responsible for the exchange of power state and control information between IHERs.
In this article, meshed community E-LAN is focused on, and the structure is shown in Fig. 2. All the IHERs are connected to their neighbor IHER(s) into the mesh structure via IICs, and the power lines between them are named “power links.” High-voltage (450 V) dc power links are adopted for transmission efficiency and system stability considerations. IICs play a vital role in distributed power management of E-LAN, which are bidirectional dc/dc power converters. They control the power amount and quality flowing into the IHERs, and two potential topologies are to be used based on different applications: Buck/Boost and DAB.

To achieve distributed power management in the E-LAN, a real-time energy routing algorithm is indispensable [13]. It requires real-time and bidirectional communication between IHERs, including: 1) intra-IHER: communications between ICs in an IHER; and 2) inter-IHERs: communication between directly connected IICs of neighbor IHERs.

In this article, by employing PSDM, all the ICs are multiplexed as data transmitters, which means no separate communication module is required, while the communication function will be embedded into power and control modules, as shown in Fig. 1(b). All the ICs are responsible for both power conversion and data modulation, whereas all the common dc buses in IHERs and power links between IHERs will transmit both power and information.

As a result, in this article, intra-IHER communication refers to bidirectional communication between the ICs and IIC within an IHER and inter-IHERs communication refers to bidirectional communication between neighbor IICs.

### III. Principle of PSDM

Using the proposed PSDM method, power conversion and data modulation can be achieved simultaneously without additional hardware circuits.

Fig. 3 shows the basic principle of the PSDM based on a power converter, in which $H(s)$ is the transfer function of the feedback network, $G_m(s)$ is the transfer function of PWM modulator, $G_{ad}(s)$ is the transfer function from duty cycle to the low-voltage side output voltage of the Buck/Boost converter, and $G_c(s)$ is the transfer function of compensator. An additional sinusoidal carrier is superimposed on the dc reference as data carrier. Data are injected into the control loop and transferred to the input–output voltage/current via the power conversion process.

Data are directly modulated to the additional sinusoidal carrier, and amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK) are the three mainstream digital data modulation approaches. ASK modulation is sensitive to noises, especially in multi-ary modulations, thus not suitable in the power converter system with much more serious noise interferences than dedicated communication systems. FSK modulation encounters the challenge of crosstalk in transmission, and its bandwidth utilization is relatively low. PSK modulation has the best noise immunity, and the bandwidth utilization is high, especially in multi-ary modulation conditions.
Fig. 4 shows the principle of 2PSK. To solve the problem of phase ambiguity and increase communication rate, improved method binary differential phase shift keying (2DPSK) modulation is employed in this article, and the principle is shown in Fig. 4(b). Phase shift relative to the previous symbol can be 0 and π, representing digital data 0 and 1, respectively.

The amplitude of communication signal is determined by both power conversion and communication qualities. Specifically, from the communication perspective, according to Shannon’s Theorem in the following equation, with a given communication bandwidth, the channel capacity $C$ is determined by the signal-to-noise ratio (SNR):

$$C = B \log_2 (1+S/N).$$  \hspace{1cm} (1)

Larger signal amplitude leads to larger SNR, and improved communication quality is achieved. From the power conversion perspective, the communication signals are the interference of the dc power, and they are usually required to be within 1% of the dc voltage. Therefore, in the determination of the communication signal amplitude, both power conversion and communication qualities should be satisfied. For some conditions when it is hard to achieve tradeoff, improved signal modulation strategies could be adopted, e.g., spread spectrum modulation can reduce the requirement on SNR by expanding the system bandwidth $B$.

In the receiver, the demodulation process is mainly composed of three steps, i.e., signal conditioning, FFT-based demodulation, and data recognition. The signal conditioning circuit is a bandpass filter to remove switching ripples and their high-order harmonics, as well as other noises. The conditioned signal is then sent to the digital processor for demodulation. In this article, the FFT algorithm is adopted to calculate the corresponding phase and amplitude of the received signals. Finally, 0–1 decision is made based on the FFT result and binary data are successfully recognized in the receiver.

In multi-machine conditions, several information flows may cause crosstalk to deteriorate the communication reliability. To solve this problem, the frequency division multiple access (FDMA) strategy is adopted, and each power converter accessing to the same common transmission line is allocated with unique and orthogonal frequency.

The frequency selection of injected carrier is another key issue in PSDM. Taking the PI voltage-controlled Buck/Boost converter (operating in Buck mode) as an example for quantitative analysis, the system diagram is shown in Fig. 5, and the transfer function from the voltage reference $V_{\text{ref}}$ to the output voltage $V_o$ is derived as follows:

$$G = H(s)G_m(s)G_vd(s)G_c(s).$$  \hspace{1cm} (2)

In a typical Buck/Boost converter, (1) can be derived as follows:

$$G = \frac{R_2 V_o}{R_1 + R_2} \frac{1}{1 + \frac{s^2}{2} + \frac{s^2LC}{K_p + K_i}} \frac{K_p + K_i}{s}.$$  \hspace{1cm} (3)

where $R_1$ and $R_2$ are sampling resistances, $V_o$ is the output voltage, $D$ is the duty cycle, $V_M$ is the peak voltage of the PWM carrier, and $K_p$ and $K_i$ are proportional and integral parameters in PI control.

With typical values adopted ($L = 300 \mu H$, $C = 330 \mu F$, $K_p = 0.48$, and $K_i = 480$), the system Bode diagram is shown in Fig. 6, and the PI control loop bandwidth is 100 Hz. Band A is within the control loop bandwidth and closed loop data signal control can be achieved, but the communication rate is
relatively low. Carrier frequency should be kept away from the resonance point, so band $B$ is unadaptable. In Band $C$, the data signal is beyond the bandwidth of the PI control loop, and decoupling of power control and communication control is achieved, which is employed in this article. In this condition, the signal frequency is much lower than the switching frequency, and thus the signal quality will not be influenced by the EMI filter. For higher frequencies close to switching frequency in band $D$, the small signal model is no longer accurate and the oscillation may occur.

IV. IMPLEMENTATION DESIGN OF DUAL MODULATION FOR ENERGY ROUTERS

As mentioned in Section II, both intra-IHER communication and inter-IHERs communication are required for energy routing in the E-LAN, as shown in Fig. 7 (IIC is a kind of IC).

A. Channel Modeling

Intra-IHER communication achieves bidirectional communication between ICs in an IHER. In the IHER, all ICs are connected in parallel and the equivalent channel model is shown in Fig. 7(a). In this model, voltage-controlled converter (converter 1) equals a voltage signal source $v_1$ when it sends data, as shown in Fig. 8(a). Correspondingly, current-controlled converters (converter 2 to converter $n$) equal current signal sources $i_2$ to $i_n$ when they send data, as shown in Fig. 8(b). When an IC receives data, it equals impedance $Z_{\sin}$, which is its input impedance from the bus side in carrier frequency, as shown in Fig. 8(c).

When the voltage-controlled IC sends data, the voltage carrier is superimposed on the common dc bus, which is

$$v_{bus} = v_{\sin}. \quad (4)$$

Similarly, when a current-controlled IC #\(m\) \((m \text{ is an integer}, \quad 2 \leq m \leq n)\) sends data, the current carrier is superimposed on the common dc bus, which is depicted as

$$i_{bus} = i_{m-sin}. \quad (5)$$

According to the model, the admittance of the common power bus is

$$G_{bus} = \sum_{1 \leq k \leq n} \frac{1}{R_k - j X_{k-sin}}. \quad (6)$$

Based on (5) and (6), the voltage of the carrier can be easily derived.

Inter-IHERs communication achieves bidirectional communication between neighbor IICs. In the E-LAN, energy routers are connected peer-to-peer via IICs into a mesh structure. Each power link is multiplexed as communication channel connecting neighbor IICs, and the equivalent channel model is shown in Fig. 7(b).

In this model, two neighbor IICs are defined as source IIC (voltage-controlled) and load IIC (current-controlled), respectively, according to the power flow direction. IIC equivalent circuit is the same as intra-IHER communication condition. Since the transmission distance between energy routers is nonignorable, power link impedance is considered in this case. Therefore, when the data are sent by source IIC converter, the carrier is superimposed on its output voltage (power link side voltage), which is

$$v_{TX} = v_1. \quad (7)$$

The voltage at load IIC (data receiver) is

$$v_{RX} = v_1 \frac{R_{sin} + jX_{sin}}{R_{sin} + jX_{sin} + R_{link} + j\omega L_{link}}. \quad (8)$$

When messages are sent by load IIC, the carrier is superimposed on its input current (power link side current), which is

$$i_{TX} = i_2. \quad (9)$$

The voltage at source IIC (data receiver) is

$$v_{RX} = i_{sin} (R_{sin} + jX_{sin}). \quad (10)$$

B. Operation Modes Analysis

In this article, all ICs adopt bridge topologies, and for IICs, two options are presented for different application requirements, which are Buck/Boost and DAB, respectively.
1) Buck/Boost IIC: The interconnection of neighbor IICs adopting Buck/Boost converters is shown in Fig. 9. MOSFET S3 (S4) is connected in series with S2 (S5) in opposite direction to achieve a bidirectional break between power bus and power link for safety and efficiency considerations. Source IIC operates in Boost mode, and output voltage (power link voltage) control is adopted, while load IIC operates in Buck mode, and input current (power link current) control is adopted.

With the employment of PSDM, there are four operation modes of the Buck/Boost converter, which are follows:

1) **Sleeping Mode**: All the MOSFETs are OFF and the power link voltage remains zero. There is no power exchange between the two neighbor IICs.

2) **Power Conversion Mode**: The Buck/Boost converter operates normally without data transmission.

3) **Data Transmission Mode**: It first requires an initial state establishment for data modulation and transmission, including three steps, which are also the communication handshake: First, MOSFET S3 in source IIC (communication initiator) is turned on to pull the power link voltage up to the power bus voltage, as the communication request; Second, the load IIC (communication receiver) operates in Boost mode to further pull up power link voltage, as the communication response. Third, the source IIC operates in Boost mode and controls its output voltage, and at the same time, the load IIC operates in Buck mode and controls its input current to a small level, as communication confirmation. To date, the initial state for data transmission has been established and communication “handshake” has been completed. Low power is transferred from source IIC to load IIC, based on which PSDM can be implemented for communication. The efficiency of this mode is relatively low, but it is a transient process before power transmission, which lasts notably short period.

4) **Power/Signal Multiplex Transmission (PIMT) Mode**: It is a combination of modes 2 and 3. Information flow is superimposed on the dc power flow, and the carrier can be superimposed on both the output voltage of source IIC converter and output current of load IIC converter.

The above four operation modes can be flexibly switched according to the conditions.

The Buck/Boost IIC supports galvanic nonisolated power conversion, and it has the advantages of simple structure, low cost, and high efficiency.

2) **Dual Active Bridge (DAB) IIC**: In DAB IIC, a high-frequency transformer $T_r$ is employed to achieve desired voltage gain and galvanic isolation.

The interconnection structure of neighbor IIC adopting DAB converters is shown in Fig. 10. By controlling the intra-bridge and inter-bridge phase shift of DAB, power flow can be controlled flexibly [30], [31].

Similar to Buck/Boost IIC, there are also four operation modes for the DAB IIC, including:

1) **Sleep Mode**: All the MOSFETs are OFF and the power link voltage remains zero. There is no power exchange between the two neighbor IICs;

2) **Power Conversion Mode**: The DAB operates normally, and the power link voltage is controlled by source IIC, while the power link current is controlled by load IIC;

3) **Data Transmission Mode**: The initial state establishment for data modulation and transmission includes two steps, which are also the communication handshake: First, source IIC (communication initiator) operates normally to pull the power link voltage up to a small and constant level, like 5 V, as communication request. Second, load IIC (communication receiver) operates normally and absorbs a small and constant current using closed loop current control, as a communication response. To date, the initial state for data transmission has been established and communication handshake has been completed. Low power is transferred from source IIC to load IIC, based on which PSDM can be implemented for communication;

4) **PIMT Mode**: It is a combination of modes 2 and 3, and the carrier can be superimposed on both the output voltage of source IIC and the output current of load IIC.

The four operation modes can be flexibly switched according to different conditions.

The DAB IIC converter provides galvanic isolation and the power link voltage is much lower in mode 3 than Buck/Boost IIC, but more complex structure and control algorithm increase the cost and deteriorate the reliability.
C. Data Frame Design

Referring to the mature routing algorithm used in the Internet, a simplified data frame of energy routing tables is designed for the small-scale community E-LAN, as shown in Fig. 11. In this application, the energy routing table is exchanged for dynamic energy routing among IHERs at the time only when the E-LAN structure is changed [joining of a new neighbor (a new IHER) in the community] or large power load/renewable energy resources are accessed/removed, which are the “second-level” or even “hour-level” events. Therefore, the communication rate of hundreds or thousands of bps can fully fulfill the requirement.

V. Experimental Verification

In order to validate the feasibility of the proposed embedded communication method applied in IHERs, a simplified prototype system with two identical IHERs #1 and #2 is constructed, as shown in Fig. 12. Each IHER consists of a dc 370-V power bus, a bidirectional dc 48-V interface using a two-stage Buck/Boost converter, a bidirectional ac 220-V interface using a full-bridge converter, and an IIC using two optional topologies of Buck/Boost and DAB, respectively. The prototype parameters are listed in Table I. All these IICs are designed of rated power of 2 kW. The power link voltage is 450 V during power transmission.

Intra-IHER and inter-IHER communications for power management are both verified by experiments.

A. Intra-IHER Communication

In this experiment, only IHER #1 is involved, and Buck/Boost converter is adopted as IIC. Fig. 13 shows the simulation result. It can be seen that a low-frequency sinusoidal carrier adopting 2PSK data modulation is superimposed to the dc power flow.

When two or more ICs send data simultaneously, the FDMA strategy is adopted. Fig. 14 shows the experimental result, of which two signal frequencies, 10 and 8.3 kHz, are employed as data carriers of two ICs, respectively. The two frequencies are orthogonal in the sampling window, and thus crosstalk is avoided in the FFT demodulation process.

B. Inter-IHERs Communication

In this experiment, IHER #1 and IHER #2 are connected via IICs, and two types of IICs are employed, respectively.

In the first condition, Buck/Boost IICs are adopted, as shown in Fig. 9. Here, four typical cases are considered and the experimental waveforms are shown in Figs. 15–18. The first case corresponds to the situation of PIMT. Initially, IHER #1 transmits 740-W ($V_{bus} = 370$ V, $I_{bus} = 2$ A) power to IHER #2 via IIC #1 and IIC #2, as shown in Fig. 15. Then, communication is carried out between IICs as shown in the zoomed-in view of the waveforms. In this case, IIC #1 controls the power link voltage and IIC #2 controls the power link current. The zoomed-in view of waveforms shows that data signal voltage is around 3 V, which is about 0.67% of power link voltage (450 V), so the effect to dc power quality can be omitted. Since IIC #1 superimposes data carrier on power link voltage, while IIC #2 superimposes data carrier

![Fig. 12. Prototype system. (a) System structure. (b) Photograph.](image)

![Fig. 13. Simulation result of intra-IHER communication.](image)

![Table I: Key Parameters of the Prototype System](table)
on power link current, the amplitudes of data carriers are not exactly the same.

The second case corresponds to the situation of the change of transmission power. The initial state is the same with the first case. IHER #2 requires additional 185-W power from IHER #1, and communication process is shown in the zoomed-in view in Fig. 16. After communication, the transmitted current increases according to the request.

The third case corresponds to the situation of data exchange without power transmissions. Fig. 17 shows the communication initial state establishment and data transmission processes. IIC #1 is the communication initiator and it turns on S3 to pull up the power link voltage to 370 V (from $t_1$ to $t_2$) as a communication request. After IIC #2 detects the request, it operates in Boost mode to further pull up power link voltage (from $t_3$ to $t_4$) as a communication response. Then, IIC #1 operates in Boost mode and increases the power link voltage to 450 V (from $t_4$ to $t_5$), and IIC #2 operates in Buck mode and absorbs a small current at the same time as communication confirmation.

To date, communication handshake has been completed and communication initial state has been established. The detailed data transmission process is shown in the zoomed-in views.
transmission at $t_1$. To release power transmission, communication is firstly carried out at $t_1$, as shown in Fig. 20, and then transmission power falls to zero. For 100-m transmission distance condition, the BER is measured as 1%, which is acceptable with proper communication protocols.

These experiments have validated the basic functions of the proposed power/data integrated IHER with Buck/Boost IICs and DAB IICs, respectively. It has been validated that four operation modes can be switched flexibly, and some typical situations and processes are focused on, including information exchange with and without power transmissions and power transmission establishment and release.

VI. CONCLUSION

This article proposes an embedded communication method based on the PSDM method for IHERs in meshed E-LAN. The sinusoidal carrier is injected into the control signal, and high cooperation and integration of power control and data modulation are achieved, ensuring synchronization between power flow and information flow. In addition, the communication is achieved without extra hardware circuits or wires, which enhances the system reliability, and decreases the system cost and complexity compared with other communication methods. In the meshed E-LAN, the proposed communication method is employed in all ICs in each energy router, and intra-IHER communication and inter-IHERs communication are achieved, which provide physical basis for distributed power management. A prototype experimental system is constructed and a series of experimental results are obtained, so the effectiveness of the proposed method is verified.

There is still some research to be conducted in the future. First, the data modulation method can be optimized, introducing improved modulation methods like quadrature amplitude modulation (QAM) and orthogonal frequency division multiplexing (OFDM) to increase the frequency band utilization. Second, all the ICs adopt bridge structures, and hardware multiplexing could be explored to improve the hardware utilization in future research.

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