Embedding OFDM-Based Carrier Communication Into Power Control Loop of Converter in DC Microgrids

Ruqi Zhang, Student Member, IEEE, Yue Hui, Jiande Wu, Member, IEEE, Ruichi Wang, Member, IEEE, Zhengyu Lin, Senior Member, IEEE, and Xiangning He, Fellow, IEEE

Abstract—In direct current (dc) microgrids, communication between converters is necessary for better power distribution and finer energy scheduling. This article proposes an orthogonal frequency division multiplexing (OFDM) based carrier communication method for dc microgrid applications. The method integrates the communication function in the process of power conversion by modulating data into power control loop. To maximize the communication rate in a narrow band limited by pulsewidth modulation control, OFDM technology is applied in the data modulation process. The data is modulated to multiple low-frequency signal carriers, then the modulated wave is added to the output of the power control loop. Since no additional component is needed for sending data, this method has the advantages of low cost and simple implementation. In order to provide theoretical guidance for system design, the dc microgrid applying the proposed method is modeled. Furthermore, important issues of the communication system are discussed, including data frame format and intersymbol interference problem. At last, a 2 kW dc microgrid experimental platform is established and 9.6 kbps communication rate with a transmission distance of 200 m is achieved, which verifies the feasibility of the proposed method.

Index Terms—Carrier communication, direct current (dc) microgrid, intersymbol interference (ISI), orthogonal frequency division multiplexing (OFDM), power control loop.

I. INTRODUCTION

POWER electronics technologies have been widely used in industrial and consumer electronics, such as photovoltaics, electric vehicles, microgrids and many other fields, for several decades. Recently, as the Internet of Things grows [1] and the smart grid emerges [2], there is an increasing demand for power electronic equipment to interact with others. Consequently, the power electronic equipment integrated with communication links is a trend for future development.

Due to the attractive characteristics, such as high efficiency, good compliance with consumer electronics and simple interface with many renewable energy sources, direct current (dc) microgrids will play a much bigger role in future distributed power systems [3]. Conventionally, a hierarchical control structure, which consists of primary, secondary, and tertiary controls, is adopted for microgrid operation [4]. Droop control method is usually employed in the primary control as its simple implementation. However, it suffers from poor voltage regulation and load sharing [3]. To solve this issue, centralized [4] or cooperative distributed control methods [5]–[9] are employed in the secondary control. By providing additional voltage restoration term to the primary control based on voltage and current information of other converters, better voltage regulation and finer power distribution can be achieved. In general, 10 kbps rate and less than 100 ms communication delay are required by dc microgrid secondary control methods [9].

In order to achieve data communication in dc microgrids, different technologies have been employed, including fieldbus, wireless communication, and power line communication (PLC). Fieldbus technologies, such as controller area network (CAN) and Profibus, require independent wiring [10], which is costly and complexes the system design. Compared with fieldbus technologies, wireless communication technologies such as WIFI, Zigbee and Bluetooth, have lower maintenance costs [11], [12]. However, they do not have good real-time control performance and are subject to interference from related frequency bands. PLC technology is another option that does not require independent wiring [13], [14]. However, additional controllers and signal coupling circuits are required, which increases the cost.

Power electronic converters have the potential of modulating information with power [15], and this feature can be explored for data communication [16]–[19]. In a pulsewidth modulation (PWM) based power converter, the frequency and the phase of the PWM carrier are two degrees of freedom, and can be used for data modulation purpose. In [16], a power/signal dual
modulation (PSDM) method was proposed. By changing the PWM carrier frequency according to the transmitting data, the frequency shift keying (FSK) data modulation is achieved, and the data can be demodulated from the input/output voltage ripples of power converter. In [17], a novel method was proposed to integrate communication with power conversion by modulating information into the spread spectrum-based PWM carrier. In [18], PSDM technique is applied in LED drives to realize visible-light communication in a cost-effective way. The above methods employ single PWM carrier for the data modulation, and are named as PSDM with single carrier (PSDM-SC) method in this article. PSDM-SC can achieve relatively high communication rate, but the data modulation methods are greatly restricted.

Another way to implement PSDM was proposed in [20]–[22] by superimposing a low-frequency signal carrier on the power control loop, and is named as power/signal dual modulation in control loop (PSDM-CL) method in this article. In [20], disturbances are added into the control loop of the photovoltaic optimizer as the data carrier, and a 2 kbps communication link among the optimizers is established. In [21], a phase-control-based freedom is introduced to the conventional phase-shifted full bridge control loop to realize communication, and the signal intensity can be regulated by the proposed perturbation depth. In [22], a power talk communication strategy is developed for dc microgrids by adding disturbance on voltage reference, which achieves communication speed of 100 to 1000 baud rate. In PSDM-CL methods, power and data modulations use different carriers, therefore many methods can be selected for data modulation.

Compared with other communication technologies, the PSDM method has the advantages of no additional wiring, less communication circuits, and low manufacturing costs.

However, in practical, the data rate and the maximum transmission distance are the major concerns for PSDM methods. For PSDM-SC method, the strength of the transmitted signal is small and cannot be adjusted, so the communication range is limited. On the contrary, PSDM-CL method proposed in [20]–[22] offers controllable transmission signal strength and longer transmission distance. Whereas, the data carrier frequency of PSDM-CL is a fraction of the PWM frequency, so that the bandwidth of the communication signal is relatively small that might not be fast enough for the demand of secondary control in dc microgrids.

Orthogonal frequency division multiplexing (OFDM) technology has the advantages of high frequency band utilization [23], which has been fully studied in the communication area but not been introduced to the PSDM-CL method yet. To increase data rate in a narrow band, this article proposes an OFDM-based PSDM-CL method to set up communication links between converters in the secondary control layer of dc microgrids. The data is modulated to multiple low-frequency signal carriers, then the modulated wave is added to the output of the power control loop. By employing OFDM in the data modulation process, the communication rate can be significantly increased and meet the demand of dc microgrid operation.

This article is organized as follows. In Section II, the fundamentals of PSDM-CL method are put forward. To increase the communication rate, the OFDM-based PSDM-CL method is proposed. In Section III, the model of the dc microgrid employing the proposed method is set up and the signal transmission gain is analyzed in detail. Furthermore, guidance for power system design is provided. In Section IV, important issues of the communication system are discussed. In Section V, the experiments based on a dc microgrid platform are carried out to verify the correctness of the theory and the feasibility of the proposed method. Finally, conclusions and prospects are given in Section VII.

The main contributions of the article are as follows.

1) For the first time, the OFDM technology is implemented in the PSDM-CL method. A 9.6 kbps communication link is achieved in a 2 kW dc microgrid system with 10 kHz narrow band width, which is significantly faster than the previous PSDM-CL methods in [20]–[22].

2) A new model of dc microgrid employing the proposed OFDM-based PSDM-CL method is established. The signal transmission gain is analyzed in detail, which offers theoretical guidance for system design.

3) To deal with different and complex communication channel characteristics in the power electronics systems embedding the proposed method, a practical intersymbol interference (ISI) evaluation approach by numerical computation is designed in this article.

II. PRINCIPLE OF OFDM-BASED PSDM-CL METHOD

A. Principle of PSDM-CL Method

In the proposed PSDM-CL system, the power converter sending out data symbols is named as data-sending converter (DSC), while the power converter receiving data is named as data-receiving converter (DRC). The data modulation process in a DSC is shown in Fig. 1. First, the baseband data is modulated as a perturbation signal s(t). In this procedure, conventional modulation methods, such as FSK, amplitude shift keying, phase shift keying (PSK), and methods of multicarrier modulation, can be employed. Then, s(t) is added to the output of power control loop v_p(t) as a PSDM-CL signal v_ps(t). Finally, v_ps(t) is compared with the triangular carrier v_tr(t) to generate a gate drive signal g(t) for the DSC. After these, the data is modulated and merged into g(t).

In a dc microgrid system, PSDM-CL technique can be adopted by the converters for communication. A simplified structure of DC microgrid is shown in Fig. 2. In the system, any converters,
including distributed generators (DGs) and power loads (PLs), can operate as a DSC or a DRC.

Generally, a dc–dc converter can be divided into three parts: input low pass filter (LPF), switching network and output LPF. In a DSC, the gate drive signal \( g(t) \), which contains data information, is amplified by the switching network as the power pulse \( A_v(t) \), which is then filtered by the output LPF. Accompanied with electric power, the data symbol is injected into the dc bus. In a DRC, the dc-bus voltage is sampled, and the data can be demodulated.

In PSDM-CL scheme, it is preferable to decouple the control of power transfer and data communication. Thus, in order to suppress the influence of power control on the data symbol, the data carrier frequency \( f_c \) should be selected above the power control loop cut-off frequency \( f_{p}\). On the other side, mixed in the output power pulse \( A_v(t) \), the data symbol is attenuated by the output LPF, so \( f_c \) should be chosen as low as possible for higher transmission gain. Considering the aforementioned factors, the data carrier frequency \( f_c \) is selected as 1/50–1/5 of the converter’s switching frequency \( f_s \).

According to above analysis, it can be concluded that the data bandwidth in PSDM-CL scheme is limited in a narrow band. In order to promote the bandwidth efficiency of the communication system, OFDM technique with multiple subcarriers is employed in this article. For each subcarrier, quadrature differential PSK (QDPSK) is selected as the band modulation method. The principles of data modulation and demodulation are discussed as follows.

**B. Data Modulation and Demodulation Principle of PSDM-CL Method Based on QDPSK-OFDM**

For an OFDM system with \( N \) subcarriers \( x_k(t) \), the modulated signal \( s(t) \) of the system can be expressed as

\[
s(t) = \sum_{k=1}^{N} x_k(t) \quad (1)
\]

\[
x_k(t) = d_k \cos(2\pi f_{ck} t + \varphi_k), \quad k = 1, 2, \ldots, N \quad (2)
\]

where \( x_k(t) \) is the \( k \)th subcarrier, and \( d_k, f_{ck}, \varphi_k \) are the amplitude, frequency, and phase of the \( k \)th subcarrier, respectively.

According to the basis of OFDM, \( x_k(t) \) should be orthogonal with each other in a single symbol period \( T_b \), which is

\[
\int_{t}^{t+T_b} \cos(2\pi f_{ck} t + \varphi_i) \cos(2\pi f_{ck} t + \varphi_j) dt = 0 \quad (3)
\]

where \( i, j = 1, 2, \ldots, N \), and \( i \neq j \). It can be deduced from (3) that \( f_{ck} \) satisfies

\[
f_{ck} = \frac{M_k}{T_b} \quad (4)
\]

where \( M_k \) are positive integers.

The process of QDPSK-OFDM includes two steps, as shown in Fig. 3. The first step is the serial-to-parallel conversion. The baseband data stream in series is redistributed to \( N \) subcarriers. The second step is the QDPSK modulation. For each subcarrier \( x_k(t) \), a quadrature bit is converted into \( M_k \) continuous sinusoidal waves in one symbol period. As the data information of the \( n \)th subcarrier in the \( n \)th symbol period, \( \text{dat}_k[n] \) determines the phase difference \( \Delta \varphi_k(n) \) of \( x_k(t) \) between the \( n \)th and \((n-1)\)th symbol period, which is

\[
\Delta \varphi_k(n) = \varphi_k(n) - \varphi_k(n-1) = \frac{\pi}{2} \text{dat}_k[n], \text{dat}_k[n] \in \{0, 1, 2, 3\}. \quad (5)
\]

The perturbation signal \( s(t) \) is the summation result of all \( x_k(t) \), which is then added to the power control loop for transmission.

Suppose a 16 Quaternary code “0312 1302 3120 1213” is transmitted in an OFDM system with four subcarriers. The waveform of \( x_4(t) \) is illustrated in Fig. 4(a). Take the fourth subcarrier \( x_4(t) \) as an example, the transmitted data is “1213,” a quadrature bit is converted into four continuous sinusoidal waves in one symbol period. The relationship among \( \varphi_4(n), \Delta \varphi_4(n) \) and \( \text{dat}_4[n] \) are as shown in Fig. 4(b).

Applying the OFDM-based PSDM-CL method in the dc microgrid and ignoring the sidebands, the spectrum of dc-bus voltage \( v_{PCC} \) is shown in Fig. 5, where \( f_g \) is the grid frequency. The frequencies of the subcarriers are orthogonal to one another. They are all far apart from the power transmission band, the grid and the switching frequency \( f_s \), which alleviates the interference from power harmonics.

The data demodulation process of the PSDM-CL method includes two steps, as shown in Fig. 3. The first step is the discrete Fourier transform (DFT). In the DRC, the dc-bus signal \( v_{PCC} \) is sent through a band pass filter (BPF) to eliminate interference. For the \( k \)th subcarrier, by performing DFT at \( f_{ck} \) on the filtered
Fig. 4. (a) Modulated subcarrier waveforms of QDPSK-OFDM and (b) Details of $x_4(t)$.

Fig. 5. Bus voltage spectrum of OFDM-based PSDM-CL converter.

signal $v_{fil}$, the phase in the $(n - 1)$th and $n$th symbol period are calculated as $\theta_k(n - 1)$ and $\theta_k(n)$ respectively, so the phase difference of the two symbols is

$$
\Delta \theta_k(n) = \theta_k(n) - \theta_k(n - 1).
$$

Based on QDPSK principle, $dat_4[n]$ is got according to $\Delta \theta_k(n)$. Finally, parallel-to-serial conversion is performed on all the received data of subcarriers, and the data can be decoded by the DRC.

III. MODELING OF DC MICROGRID APPLYING THE PROPOSED METHOD

In general, the characteristics of the communication channel would affect the performances of communication system. In the dc microgrid system, the impedance of the power electronic converter is the key determinant for the channel characteristics. Thus, it is necessary to model the dc microgrid system and analyze the impedance of the communication channel.

Considering the cable impedance, the equivalent model of a typical dc microgrid system is shown in Fig. 6. The system consists of $n_1$ DGs and $n_2$ PLs, and PCC is the point of common coupling in the system. $Z_{l,DG}$ and $Z_{l,PL}$ are the equivalent cable impedance from DG #i and PL #j to PCC respectively. The DGs can be simplified by using Thevenin’s equivalent theorem, as shown in Fig. 6, where $v_{o,DGi}$ and $Z_{oc,DGi}$ are the voltage source and output impedance of DG #i in Thevenin equivalent model, respectively. For PL #j, the closed-loop input impedance is denoted as $Z_{ic,PL}$. Since the distributed cable capacitance is small, it is merged to the input and output impedance of DGs and PLs.

For convenience, assume that the dc microgrid operates in island mode without grid-connected inverters. Suppose DG #1, which is a droop-controlled boost converter, performs as the DSC, and PL #1, which is a buck converter, performs as the DRC. Compared with the power modulation signal, the communication carrier is a small perturbation. Since $f_c$ is less than $f_s/5$, the traditional small signal analysis is applicable.

In the proposed method, the duty perturbation at $f_c$ in power control loop corresponds to the amplitude of OFDM subcarriers with the same frequency. The signal transmission gain from DSC to DRC, is defined as $G_{sig}$ in (7), where $\hat{d}$ is the perturbation signal added to the control loop in DSC, and $\hat{v}_{sig}$ is the signal received by DRC. $G_{sig}$ is the most important parameter for the PSDM-CL system and will be analyzed in detail.

$$
G_{sig}(s) = \frac{\hat{v}_{sig}}{\hat{d}}.
$$

The detailed control block diagram of DG #1 is illustrated in Fig. 7(a), where $V_{o1}$ is the reference voltage without load, and $r_d$ is the droop coefficient. The control scheme consists of three loops, the drooped-control outer loop, the voltage loop and the inductor current inner loop. The related transfer functions (TFs) are listed as follows.

- $G_v$: Compensation TF of voltage loop.
- $G_i$: Compensation TF of inductor current loop.
- $G_{delay}$: TF of the digital control delay link.
- $G_{id}$: TF from the duty cycle to inductor current $\hat{i}_L$.
- $G_{iio}$: TF from $i_{o1}$ to $\hat{i}_L$.
- $G_{vio}$: TF from $\hat{i}_L$ to $\hat{v}_{o1}$.

Referring to [24], the expressions of $G_{id}$, $G_{iio}$, and $G_{vio}$ are calculated as in (8), where $D_{o1}$ is the duty cycle of $S_2$ in steady state, $I_{o1}$ and $V_{o1}$ are the dc output current and voltage respectively.
The frequency of data carrier $f_c$ is beyond the cut-off frequency characteristics of $G_{\text{sig}}$ with different $l_{\text{PL1}}$, which corresponds with the characteristics of output LPF. Also, at a given $f_c$, $|G_{\text{sig}}|$ is negatively correlated with $C_o$, which indicates that reducing the capacitance of the converter at the bus port could improve the signal transmission gain.

However, in most applications of dc microgrids, the line impedance cannot be ignored. In this article, the impedance of the power line is assumed to be

$$Z_{\text{load}} = Z_{\text{L.P.L1}} + Z_{\text{PCC}}.$$  

where $l_{\text{P.L1}}$ is the length of the power line in meters, the gain-frequency characteristics of $G_{\text{sig}}$ with different $l_{\text{P.L1}}$ is plotted in Fig. 9. It can be observed that the communication signal
is reduced with the increasing of \( I_{PL1} \). In addition, the decay rate of \(|G_{\text{sig}}|\) is about 60 dB/10 dec in frequency domain. Thus, the higher-frequency subcarriers would be attenuated more seriously in the communication channel.

In order to increase the signal transmission gain of high-frequency subcarriers in long-distance applications, an inductor \( L_M \) can be added at the bus port of the converter, as suggested in Fig. 6. The existence of \( L_M \) increases \( Z_{ic,c,L1} \) and thereby increasing \(|G_{\text{sig}}|\) according to (18). Fig. 10 shows the gain-frequency characteristics with added \( L_M \). It can be observed that \( L_M \) promotes the signal transmission gain at high frequencies. However, an additional zero at \( f_c \) is introduced by the resonance of \( L_M \) and the input capacitor \( C_{bus,PL1} \) of DRC. To reduce the impact on the communication, \( f_c \) should be assigned to a frequency lower than the OFDM spectrum. Besides, the power transmission band is typically from dc to several hundred hertz. In order to reduce the impact on power control, it is preferable to set \( f_c \) higher than the power transmission band. The detailed method is out of the scope of this article, and will not be discussed.

IV. COMMUNICATION SYSTEM CONSIDERATIONS

A. Frame Format Design

According to the above analysis, the transmission gain and delays of subcarriers in the channel are different, which causes ISI and intercarrier interference (ICI). In OFDM technology, a cyclic prefix (CP) is usually added to eliminate ICI, reduce ISI and improve the signal-to-noise ratio (SNR). This method is adopted by this article, and the communication frame format is shown in Fig. 11. For simplicity, only one subcarrier is plotted. Each frame format consists of one synchronization symbol and \( N_{\text{data}} \) data symbols. The synchronization symbol and the data symbol (including CP) have the same duration, which is \( T_b \). The synchronization symbol performs as the frame header, marking the beginning of a frame. The data is firstly distributed to \( N \) subcarriers, and then modulated into the periods of data symbols according to QDPSK principle, as discussed in Section II. The detailed communication process is illustrated as follows.

First, the synchronization symbol is sent from the transmitter to the receiver. The carrier frequency used by the synchronization bit is generally selected among OFDM subcarrier frequencies \( f_{c1} \sim f_{cN} \). The receiver detects the amplitude of the synchronization signal through a sliding window DFT algorithm to achieve frame synchronization.

Then, \( N_{\text{data}} \) data symbols are transmitted in sequence. Each data symbol is composed of a CP and a DFT period, denoted as \( T_{\text{CP}} \) and \( T_{\text{DFT}} \) respectively. The lengths of CP and DFT period should satisfy

\[
T_b = T_{\text{CP}} + T_{\text{DFT}}.
\]

The phase of each subcarrier is continuous during \( T_{\text{CP}} \) and \( T_{\text{DFT}} \), which ensures the correctness of demodulation results even if the DFT window at the receiver is not completely aligned with \( T_{\text{DFT}} \).

The performance of OFDM communication is greatly affected by system parameters, including subcarrier frequency spacing \( \Delta f_c \) and CP length \( T_{\text{CP}} \).

In general, the subcarrier spacing \( \Delta f_c \) is set with respect to \( T_{\text{DFT}} \), which is

\[
\Delta f_c = \frac{M_s}{T_{\text{DFT}}},
\]

where \( M_s \) is a positive integer. In order to achieve maximum band utilization in a narrow band, \( M_s \) is set to 1 in the proposed method, thus \( \Delta f_c \) is \( 1/T_{\text{DFT}} \).

In order to eliminate ICI caused by the multipath delay of subcarriers in the communication channel, \( T_{\text{CP}} \) must be greater than the maximum multipath delay, which is

\[
T_{\text{CP}} > \max \left\{ \frac{1}{2 \pi f_c} \angle G_{\text{sig}}(2 \pi f_c) \right\} - \min \left\{ \frac{1}{2 \pi f_c} \angle G_{\text{sig}}(2 \pi f_c) \right\}.
\]

B. ISI Evaluation

Conventionally, ISI for a communication system is analyzed and evaluated in time domain, which is rather complicated. In order to deal with different and complex communication channel characteristics in the power electronics systems with the proposed OFDM-based PSDM-CL technique, a practical ISI evaluation method is designed as following.

In an OFDM system, the subcarrier \( x_k \) in the \( n \)th symbol period suffers interference from previous symbols due to the nonideal characteristic of the communication channel, which is defined as ISI. For subcarrier \( x_k \), ISI originates from two parts, which are interference from itself and from other subcarriers. The latter
can be easily eliminated by adding a CP, and this article will focus on evaluating ISI from itself.

In general, the ISI is mainly from adjacent symbol. In the \( n \)th symbol period, the \( k \)th subcarrier signal \( x_k(t) \) to be transmitted is the result of multiplying the ideal sine wave \( w_k(t) \) and the rectangular window \( r_1(t) \) in time domain, as shown in Fig. 12

\[
x_k(t) = w_k(t) r_1(t).
\]  

(24)

The expression of \( r_1(t) \) is

\[
r_1(t) = \begin{cases} 
1, & -\frac{T_{DFT}}{2} < t < \frac{T_{DFT}}{2} \\
0, & t \geq \frac{T_{DFT}}{2} \text{ or } t < -\frac{T_{DFT}}{2}.
\end{cases}
\]  

(25)

The TF of the channel is composed of signal transmission gain \( G_{\text{sig}}(\omega) \) and the signal filter \( G_{\text{fil}}(\omega) \) at the receiver. Passing through the channel, the received signal \( y_k(t) \) is

\[
y_k(t) = F^{-1}[Y(w)] = F^{-1}\{F[x_k(t)]G_{\text{sig}}(w)G_{\text{fil}}(w)\}.
\]  

(26)

By performing DFT algorithm on \( y_k(t) \), the demodulated results at \( f_{ck} \) in the \( n \)th symbol period can be calculated as

\[
Y_{R1}(w) = Y(w) * R_1(w).
\]  

(27)

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\[
Y_{R1}(w) = Y(w) * R_1(w).
\]  

(27)

The nth symbol will interfere the demodulation of the \((n+1)\)th symbol. By adding a delayed rectangular window \( r_2(t) \) to \( y_k(t) \) and performing DFT, the received signal can be calculated as

\[
Y_{R2}(w) = F[y_{k,r2}(t)] = F[y_k(t) r_2(t)] = Y(w) * R_2(w).
\]  

(28)

The relationship between \( r_2(t) \) and \( r_1(t) \) is

\[
r_2(t) = r_1(t - T_b).
\]  

(29)

The analytical expressions of (27) and (28) are often complex or even unsolvable. Therefore, in practical, numerical calculation tools such as MATLAB can be used to calculate \( Y_{R1}(\omega) \) and \( Y_{R2}(\omega) \). Define \( \alpha \) as

\[
\alpha = \frac{|Y_{R2}(\omega)|}{|Y_{R1}(\omega)|}.
\]  

(30)

Obviously \( \alpha \) represents the severity of ISI. The higher the value of \( \alpha \), the more serious the ISI problem will be. The ISI of the proposed system will be evaluated in Section V-A by calculating \( \alpha \) and the maximum angle error \( \theta_e \).

V. EXPERIMENTAL RESULTS

A. Experimental Setup

The feasibility of the PSDM-CL method and the correctness of the theoretical analysis have been experimentally verified on a 2 kW dc microgrid experimental platform. The platform structure and photo are shown in Figs. 13 and 14, respectively. The dc microgrid includes two DGs with boost topology and two PLs with buck topology. DG #1 performs as DSC and PL #1 performs as DRC. TMS320F28377 from Texas Instruments is used for each power converter to implement the control algorithm and the proposed OFDM-based PSDM-CL method. 200-meters cables are used to connect PCC and PL #1 to test the communication performance with long cables.
The experimental parameters of the dc microgrid and the communication system are given in Tables I and II, respectively. It should be noted that $L_M$ is only for the experiment in Section V-D. In this platform, the converter’s power control loop cut-off frequency is set to 2 kHz, while the communication carrier frequencies are selected above 3 kHz to decouple power conversion and data communication.

In order to meet the communication rate requirement of secondary control in dc microgrid, the DFT period is set to 0.2 ms to eliminate ICI. Six subcarriers, $x_1 \sim x_6$, are used for OFDM modulation on each subcarrier modulation waveforms, respectively, are expressed by $v_{\text{ps}}(t)$ and $v_{\text{sig}}(t)$, which have been explained in Section II. It can be observed that the severity of ISI decreases as $f_c$ increases. The maximum angle error caused by ISI is $7.56^\circ$, which is much smaller than $45^\circ$. Hence, the SNR can be guaranteed when QDPSK is applied in the experiment.

**B. System Modeling Experimental Verification**

This experiment aims to check the correctness of system modeling in Section III. In this test, the length of the cable $l_{PL1}$ is 1 meter. The peak value of $\hat{v}_{\text{sig}}$ is measured at PL #1 when perturbation $\tilde{d}$ is added to the control loop in DG #1. The theoretical and experimental results of $|G_{\text{sig}}|$ are calculated and plotted, as shown in Fig. 15(b). It can be observed that the experimental result is almost in line with the theoretical one, which verifies the correctness of the system modeling. It is also clear that $|G_{\text{sig}}|$ gradually decreases as the frequency increases. In order to compensate for the attenuation of higher-frequency subcarriers, a viable option is to increase the perturbation amplitudes of higher-frequency subcarriers.

**C. System Performance Test With Short Cable**

In this experiment, the power transfer and communication functions of the dc microgrid system are tested. The length of the cable $l_{PL1} = 1$ m. The dc microgrid is operated in steady state. DG #1 and DG #2 are transferring a total power of 2 kW to the PLs, and each PL consumes a fixed power of 1 kW.

In this case, DG #1 sends a set of test data $d_{\text{ck}}$ [8], repeated to other power converters via the dc bus. The subcarrier frequency $f_{ck}$, perturbation amplitude $d_k$ and quaternary data sent by each subcarrier are matched in Table III. According to (16), the maximum perturbation of $v_{\text{PCC}}$ introduced by the communication is 489 mV. This value meets the power quality requirements of the dc microgrid.

Fig. 16 depicts the modulation waveforms of DG #1 when it is sending $d_{\text{ck}}$ [8], $x_1(t)$ and $x_4(t)$, which are the first and fourth subcarrier modulation waveforms, respectively, are expressed by the outputs of digital-to-analog conversion (DAC) module. $v_{\text{ps}}(t)$ is the DAC output of $s(t)$, which has been explained in Section II. $v_{\text{PCC,DG1}}$ is the ac component of $v_{\text{PCC,DG1}}$. It can be observed that the carrier frequency used by the synchronization symbol is 3 kHz, and the waveforms of $x_1(t)$, $x_4(t)$, and $v_{\text{ps}}(t)$ are matched with the theory in Section II.

Fig. 17 demonstrates the operation states of the dc microgrid. It can be observed that $V_{\text{PCC,DG1}}$ is around 370 V. The ac
component $\tilde{v}_{PCC,DG1}$ has a peak-to-peak amplitude of around 1.2 V. The load current of PL #1 $I_{o,PL1}$ is about 5 A, which corresponds to 1 kW load. The fluctuation of $v_{PCC,DG1}$ introduced by communication does not exceed 1 V. The filtered signal $v_{fil}$ is obtained by passing through a BPF from $v_{PCC,PL1}$, and it is ready for demodulation.

At PL #1, demodulation algorithm is performed by the microcontroller, and the results of the subcarrier data are expressed by the outputs of DAC module, as shown in Fig. 18. The results are consistent with Table III, which proves the effectiveness of the proposed communication method. The signals of CH2–CH7 lag about $T_{DFT}$ behind the signal of CH1, which is because the controller needs to perform DFT within a complete $T_{DFT}$.

Besides, the frequency spectrum of $v_{fil}$ is shown in Fig. 19. The frequency band of the fast Fourier transform results is distributed between 2.5 and 8.5 kHz. The frequency band is relatively flat, which verifies the relevant analysis in Section III.

### D. System Performance Test With Long Cable

This experiment aims to test the communication function under the circumstances of long transmission distance. In this case, $l_{PL1}$ is set to 200 m. In order to increase the input impedance of converters, $L_M$ is added at the bus port of every converter.

As an example, a simple communication protocol is designed. In the protocol, subcarrier $x_1$ and $x_2$ are arranged to represent the command type and value respectively, while subcarrier $x_3$ is reserved for the summation check results of $x_1$ and $x_2$. Subcarrier $x_4$, $x_5$, and $x_6$ are not used in the simple protocol. They can be used in more complicated protocols for advanced dc microgrid secondary control.

In this experiment, DG #1 performs as the master and sends a command frame to change the output power of PL #1 by the proposed OFDM-based PSDM-CL method. The detailed parameters of the command frame are illustrated in Table IV. In order to promote the signal strength at DRC, $d_k$ is set larger than that in the experiment of Section V-C. The command type 0x03 in the subcarrier $x_1$ represents that DG #1 orders PL #1 to regulate its output power to the given value. The given value is 600 W, which is expressed by the subcarrier $x_2$. As the slave, PL #1 samples the bus voltage, demodulates the data frame and regulates its output power according to the command.

Fig. 20 depicts the waveforms of the above process. $v_{fil}$ is the filtered signal obtained by passing through a BPF from $v_{PCC,PL1}$. The initial operation state of dc microgrid is the same as that in Section V-C. The output power of PL #1 is 1 kW. At $t_0$, a command frame is sent by DG #1. Starting from $t_1$, PL #1 successfully receives the command frame and regulates its output power to 600 W according to the data information.

In order to clarify the details of the communication process, the command frame in Fig. 20 is zoomed in, along with its...
demodulation results, as shown in Fig. 21. The demodulation results are the same with dat[8] in Table IV, which proves the feasibility of the proposed method under the circumstances of long transmission distance.

Furthermore, the enlarged waveforms of \( \hat{v}_{PCC, DG1} \) and \( \hat{v}_{PCC, PL1} \) during the communication process are illustrated in Fig. 22. The ac amplitude of \( \hat{v}_{PCC, PL1} \) is about 2/5 that of \( \hat{v}_{PCC, DG1} \), which is consistent with the analysis in Section III. Whereas, due to the existence of \( L_M \), the signal is still large enough to be correctly demodulated by the DRC.

VI. CONCLUSION

This article analyzes the principles and implementations of OFDM-based PSDM-CL method and validates its feasibility in the dc microgrid. A practical evaluation method for ISI was designed, which can be promoted to all power electrical systems applying the OFDM-based PSDM-CL method. A communication rate of 9.6 kbps was achieved in a 2 kW dc microgrid, which meets the requirements of microgrid applications. Since no additional communication controllers and less communication components were required by the proposed method, it has the advantages of low costs and simple implementation, and therefore has broad application prospects.

Nevertheless, the proposed method introduced in this article was improved in many aspects. First, advanced techniques used in conventional OFDM, such as equalization and peak-to-average-power-ratio suppression techniques, was adopted to deal with complicated operating conditions. Second, in practical, communication failure might occur due to complex power transfer situations. In this case, automatic repeat request mechanism was employed to deal with the communication failure. Third, in long-distance communication applications, additional impedance-match components were required to promote the signal transmission gain of high-frequency subcarriers, which is worth further research.

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Ruqi Zhang (Student Member, IEEE) was born in Fujian, China, in 1994. He received the B.S. degree in electrical engineering in 2016 from Zhejiang University, Hangzhou, China, where he is currently working toward the Ph.D. degree in electrical engineering at the College of Electrical Engineering, Zhejiang University. From September 2015 to June 2016, he was an Intern with Silan Microelectronics Co. Ltd., Hangzhou. His current research interests include communication techniques applied in distributed power electronics system.

Jiande Wu (Member, IEEE) was born in Zhejiang, China, in 1973. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the College of Electrical Engineering, Zhejiang University, Hangzhou, China, in 1994, 1997, and 2012, respectively. Since 1997, he has been a Faculty Member with Zhejiang University, where he is currently an Associate Professor. From 2013 to 2014, he was an Academic Visitor with the University of Strathclyde, Glasgow, U.K. His research interests include power electronics control, distributed power electronics system and fieldbus communication.

Yue Hui received the B.S. degree in electrical engineering in 2020 from Zhejiang University, Hangzhou, China, where she is working toward the M.S. degree in electrical engineering at the College of Electrical Engineering, Zhejiang University. Her current research interests include distributed power electronics system.

Zhengyu Lin (Senior member, IEEE) received the B.Sc. and M.Sc. degrees from the College of Electrical Engineering, Zhejiang University, Hangzhou, China, in 1998 and 2001, respectively, and the Ph.D. degree from Heriot-Watt University, Edinburgh, U.K., in 2005, all in electrical engineering.

Since 1997, he has been a Senior Lecturer with the School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, U.K. He is currently holding an EPSRC UKRI Innovation Fellowship on DC microgrids. His current research interests include power electronics and its applications in renewable energy, energy storage, motor drives, microgrids, and multienergy systems.

Xiangning He (Fellow, IEEE) was born in Fujian, China, in 1969. He received the B.S. and M.Sc. degrees from the Nanjing University of Aeronautical and Astronautical, Nanjing, China, in 1982 and 1985, respectively, and the Ph.D. degree from Zhejiang University, Hangzhou, China, in 1998. He was an Associate Professor with Zhejiang University since 1997, where he has been a Full Professor with the College of Electrical Engineering, Zhejiang University. His research interests are power electronics and their industrial applications.

Dr. He was an IEEE Distinguished Lecturer for the IEEE Power Electronics Society in 2011. He is also a Fellow of the Institution of Engineering and Technology (formerly IEE), U.K. He was the recipient of the Fellowship from the Royal Society of U.K., in 1991.