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

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Abstract—In direct current (DC) microgrids, communication between converters is necessary for better power distribution and finer energy scheduling. This paper 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 PWM 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 inter-symbol interference (ISI) 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, orthogonal frequency division multiplexing (OFDM), DC microgrid, power control loop, inter-symbol interference (ISI).

I. INTRODUCTION

POWER electronics technologies have been widely used in industrial and consumer electronics, such as photovoltaics, electric vehicles (EVs), microgrids and many other fields, for several decades. Recently, as the Internet of Things (IoT) 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 100ms 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 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 pulse-width 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 power/signal dual

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modulation with single carrier (PSDM-SC) method in this paper. 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 paper. In [20], disturbances are added into the control loop of the photovoltaic optimizer as the data carrier, and a 2kbps 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, which 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 be introduced to the PSDM-CL method yet. To increase data rate in a narrow band, this paper 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 paper 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 paper are as follows.

Fig. 1. Data modulation process in a DSC.

Fig. 2. Simplified structure of a DC microgrid system.

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 bandwidth, 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 inter-symbol interference (ISI) evaluation approach by numerical computation is designed in this paper.

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 (ASK), phase shift keying (PSK), and methods of multi-carrier modulation, can be employed. Then, $s(t)$ is added to the output of power control loop $v_p(t)$ as a PSDM-CL signal $v_{ps}(t)$. At last, $v_{ps}(t)$ is compared with the triangular carrier $v_{tri}(t)$ 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.

Fig. 3. Communication process of OFDM-based PSDM-CL method.

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 $A_o(t)$, 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 $A_o(t)$, 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 $1/50 \sim 1/5$ 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 paper. For each subcarrier, quadrature differential phase shift keying (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

$$s(t) = \sum_{k=1}^N x_k(t), \quad (1)$$

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

where $x_k(t)$ is the k^{th} subcarrier, and d_k, f_{ck}, φ_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

$$\int_t^{t+T_b} \cos(2\pi f_{ci}t + \varphi_i) \cos(2\pi f_{cj}t + \varphi_j) dt = 0, \quad (3)$$

where $i, j=1, 2, \dots, N$, 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 OFDM

 Fig. 4(a). Modulated subcarrier waveforms of QDPSK-OFDM (b) Details of $x_4(t)$.

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

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 k^{th} subcarrier in the n^{th} symbol period, $data_k[n]$ determines the phase difference $\Delta\varphi_k(n)$ of $x_k(t)$ between the n^{th} and $(n-1)^{\text{th}}$ symbol period, which is

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

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 being transmitted in an OFDM system with 4 subcarriers. The waveform of $x_k(t)$ 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 4 continuous sinusoidal waves in one symbol period. The relationship among $\varphi_4(n)$, $\Delta\varphi_4(n)$ and $data_4[n]$ 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 frequency f_g 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

Fig. 6. Equivalent model of a typical DC microgrid.

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 signal v_{fil} , the phase in the $(n-1)^{\text{th}}$ 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

$$\Delta\theta_k(n) = \theta_k(n) - \theta_k(n-1). \quad (6)$$

Based on QDPSK principle, $data_k[n]$ 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_DGi} and Z_{L_Lj} 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_Lj} . 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

Fig. 7. Control block diagram of DG #1 (a) Complete model. (b) Simplified model.

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.

$$G_{sig}(s) = \frac{\hat{v}_{sig}}{\hat{d}} \quad (7)$$

The detailed control block diagram of DG #1 is illustrated in Fig. 7(a), where $\hat{V}_{o1}$ 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 $\hat{i}_{o1}$ to $\hat{i}_L$.

G_{vio} : TF from $\hat{i}_{o1}$ to $\hat{v}_{o1}$.

G_{vi} : TF from $\hat{i}_L$ to $\hat{v}_{o1}$.

Referring to [24], the expressions of G_{id} , G_{iio} , G_{vio} , and G_{vi} are calculated as in (8), where D_p is the duty cycle of S_2 in steady state, I_{o1} and V_{o1} are the DC output current and voltage of DG #1.

$$\begin{cases} G_{id}(s) = \frac{sC_o V_{o1} + I_{o1}}{s^2 LC_o + (1 - D_p)^2} \\ G_{iio}(s) = \frac{1 - D_p}{s^2 LC_o + (1 - D_p)^2} \\ G_{vi}(s) = \frac{-sL I_L + V_{in}}{sC_o V_{o1} + I_{o1}} \\ G_{vio}(s) = \frac{-V_{o1}}{sC_o V_{o1} + I_{o1}} \end{cases} \quad (8)$$

The output impedance of DG #1 can be expressed as (9), where T_v and T_i are the open-loop gain of the voltage and current control loop, respectively.

$$Z_{oc\_DG1} = \frac{r_d T_v - G_{vio}(1 + T_i) - G_{iio} G_{vi}}{1 + T_i + T_v} \quad (9)$$

$$T_v = G_v G_i G_{delay} G_{id} G_{vi} \quad (10)$$

$$T_i = G_i G_{delay} G_{id} \quad (11)$$

 Fig. 8. Relationship among $|G_{sig}|$, C_o and f_c ignoring line impedance.

For DG # i and PL # j , the equivalent impedance Z_{DGi} and Z_{Lj} seen from PCC are

$$Z_{DGi} = Z_{L_{DGi}} + Z_{oc_{DGi}}, \quad (12)$$

$$Z_{Lj} = Z_{L_{Lj}} + Z_{ic_{Lj}}. \quad (13)$$

Therefore, the equivalent input impedance of the rest converters seen from PCC is

$$Z_{PCC} = 1 / \left(\sum_{i=2}^{n_1} 1/Z_{DGi} + \sum_{j=1}^{n_2} 1/Z_{Lj} \right). \quad (14)$$

So, the load impedance of DG #1 can be written as

$$Z_{load} = Z_{L_{DG1}} + Z_{PCC}. \quad (15)$$

Since the frequency of data carrier f_c is beyond the cut-off frequency of power control loop f_p , the branches of the feedback, including droop-control loop, voltage loop and current loop, can be ignored at f_c . Thus, the control diagram can be simplified as Fig. 7(b), and the transfer function between $\hat{d}$ and $\hat{v}_{o1}$ can be derived as

$$\frac{\hat{v}_{o1}}{\hat{d}} = G_{delay} G_{id} G_{vi}. \quad (16)$$

The transfer function from $\hat{v}_{o1}$ to $\hat{v}_{sig}$ is

$$\frac{\hat{v}_{sig}}{\hat{v}_{o1}} = \frac{\hat{v}_{sig}}{\hat{v}_{PCC}} \frac{\hat{v}_{PCC}}{\hat{v}_{o1}} = \frac{Z_{ic_{L1}}}{Z_{L_{L1}} + Z_{ic_{L1}}} \frac{Z_{PCC}}{Z_{load}}. \quad (17)$$

By combining (16) and (17), the signal transmission gain is

$$G_{sig}(s) = \frac{\hat{v}_{sig}}{\hat{d}} = \frac{Z_{ic_{L1}} Z_{PCC} G_{delay} G_{id} G_{vi}}{(Z_{L_{L1}} + Z_{ic_{L1}}) Z_{load}}. \quad (18)$$

Ignoring the line impedance, (18) can be simplified as

$$G_{sig}(s) = G_{delay} \frac{-s L L_L + V_{in}}{s^2 L C_o + (1-D_p)^2}. \quad (19)$$

It can be deduced from (19) that $|G_{sig}|$ is determined by the inductance L and capacitance C_o of DG #1 at a fixed output power. In the proposed system, capacitor C_o should be designed to fit for the required signal strength. The relationship among $|G_{sig}|$, capacitance C_o and carrier frequency f_c are shown in Fig. 8. It can be observed that $|G_{sig}|$ decreases as f_c increases, which corresponds with the characteristics of output LPF. Also, at a given f_c , $|G_{sig}|$ 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 paper, the impedance of the power line is assumed to be

$$Z_{L_{PL1}} = (0.009 + 3 \times 10^{-7} s) * l_{PL1}, \quad (20)$$

 Fig. 9. Gain-frequency diagram of $G_{sig}(s)$ with different power line length.

 Fig. 10. Gain-frequency diagram of $G_{sig}(s)$ with and without L_M .

where l_{PL1} is the length of the power line in meters, the gain-frequency characteristics of G_{sig} with different l_{PL1} is plotted in Fig. 9. It can be observed that the communication signal is reduced with the increasing of l_{PL1} . In addition, the decay rate of $|G_{sig}|$ is about 60dB/10dec 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 $Z_{ic_{L1}}$ and thereby increasing $|G_{sig}|$ 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_r 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_r 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_r higher than the power transmission band. The detailed method is out of the scope of this paper, 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 inter-carrier 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 paper, 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_{data} data symbols. The synchronization symbol and the data

Fig. 11. Structure of frame format.

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

$$T_b = T_{\text{CP}} + T_{\text{DFT}}. \quad (21)$$

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

The performance of OFDM communication is greatly affected by system parameters, including subcarrier frequency spacing Δf_c and cyclic prefix length T_{CP} .

In general, the subcarrier spacing Δf_c is set with respect to T_{DFT} , which is

$$\Delta f_c = \frac{M_s}{T_{\text{DFT}}}, \quad (22)$$

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 Δf_c is $1/T_{\text{DFT}}$.

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

$$T_{\text{CP}} > \max \left\{ \frac{1}{2\pi f_c} \angle G_{\text{sig}}(2\pi f_c) \right\} - \min \left\{ \frac{1}{2\pi f_c} \angle G_{\text{sig}}(2\pi f_c) \right\}. \quad (23)$$

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

Fig. 12. Signal transformation process in time and frequency domain.

non-ideal 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 paper 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.

$$x_k(t) = w_k(t)r_1(t) \quad (24)$$

The expression of $r_1(t)$ is

$$r_1(t) = \begin{cases} 1, & -\frac{T_{\text{DFT}}}{2} < t < \frac{T_{\text{DFT}}}{2} \\ 0, & t \geq \frac{T_{\text{DFT}}}{2} \text{ or } t < -\frac{T_{\text{DFT}}}{2} \end{cases}. \quad (25)$$

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

$$y_k(t) = F^{-1}[Y(\omega)] = F^{-1}\{F[x_k(t)] G_{\text{sig}}(\omega) G_{\text{fil}}(\omega)\}. \quad (26)$$

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

$$Y_{R1}(\omega) = Y(\omega) * R_1(\omega). \quad (27)$$

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

$$Y_{R2}(\omega) = F[Y_{k\_r2}(t)] = F[y_k(t)r_2(t)] = Y(\omega) * R_2(\omega). \quad (28)$$

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

$$r_2(t) = r_1(t - T_b). \quad (29)$$

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 α as

$$\alpha = \frac{|Y_{R2}(\omega)|}{|Y_{R1}(\omega)|}. \quad (30)$$

Obviously α represents the severity of ISI. The higher the value of α , the more serious the ISI problem will be. The ISI of the proposed system will be evaluated in Section V.A by calculating α and the maximum angle error θ_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

Fig. 13. Structure of experimental platform.

Fig. 14. Photo of experimental platform.

TABLE I
PARAMETERS OF DC MICROGRID SYSTEM

Description	Symbol	Value
Input voltage of DG #1, DG #2	V_{DG1}, V_{DG2}	120-200V
Bus voltage reference without load	$\hat{V}_{o1}$	380V
Output voltage of PL #1, PL #2	V_{o_PL1}, V_{o_PL2}	150-200V
Load of PL #1, PL #2	R_1, R_2	40 Ω
Droop coefficient	r_d	3V/A
Switching frequency	f_s	50kHz
Output capacitance of DG #1, DG #2	C_{bus1}, C_{bus2}	100 μ F
Input capacitance of PL #1, PL #2	C_{bus3}, C_{bus4}	100 μ F
Output capacitance of PL #1, PL #2	C_{o_PL1}, C_{o_PL2}	300 μ F
Inductance	L_1, L_2, L_3, L_4	2mH
Power line length between PCC and PL #1	l_{PL1}	1-200m
Inductance for impedance matching	L_M	40 μ H

TABLE II
PARAMETERS OF COMMUNICATION SYSTEM

Description	Parameters	Value
Number of subcarriers	N	6
Frequencies of subcarriers	$f_{c1} \sim f_{cN}$	3-8kHz
Symbol period	T_b	1.2ms
CP period	T_{CP}	0.2ms
DFT period	T_{DFT}	1ms
Communication baud rate	R_B	9.6kbps
Frequency of the synchronization symbol	f_{synch}	3kHz
Number of data symbols in one frame	N_{data}	9
Frame duration	T_{frame}	12ms

structure and photo are shown in Fig. 13 and Fig. 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 provided in Table I and Table 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 2kHz, while the

Fig. 15. (a) Simulation results of ISI evaluation. (b) Comparison of theoretical and experimental $|G_{sig}|$.

communication carrier frequencies are selected above 3kHz 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 1ms. Besides, the frame duration is 12ms, which is much less than 100 ms, i.e., the real-time transmission requirement of secondary control. According to (23), the maximum multipath delay is 0.089ms. Thus, a cyclic prefix T_{CP} is set to 0.2ms to eliminate ICI. Six subcarriers $x_1 \sim x_6$ are used for OFDM modulation on DG #1 and each subcarrier is modulated by QDPSK. Thus, each subcarrier in one frame contains 16-bits data information according to QDPSK principle. The communication baud rate of the experimental platform is

$$R_B = \frac{6 \times \log_2 4}{1.2 \times 10^{-3}} = 9.6 \text{ kbps}. \quad (31)$$

Before the experimental study, a MATLAB/Simulink model of the communication system is built to evaluate ISI based on Section IV. C. Based on the simulation results, the relationship among α , θ_e and f_{ck} is plotted in Fig. 15(a). It can be observed that the severity of ISI decreases as f_c increases. The maximum angle error caused by ISI is 7.56°, which is much smaller than 45°. 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 $\hat{v}_{sig}$ is measured at PL #1 when perturbation $\hat{d}$ is added to the control loop in DG #1. The theoretical and experimental results of $|G_{sig}|$ 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 $|G_{sig}|$ 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 $l_{PL1} = 1\text{m}$. 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 $dat_k[8]_1$ repeatedly 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 shown in Table III. According to (16), the maximum perturbation of v_{PCC} introduced by the

TABLE III
PARAMETERS OF SUBCARRIERS IN SECTION V.C

Subcarrier	f_{ck}	d_k	$dat_k[8]_1$
x_1	3kHz	0.028	01112110
x_2	4kHz	0.032	22102012
x_3	5kHz	0.032	11112222
x_4	6kHz	0.034	01332330
x_5	7kHz	0.036	23121032
x_6	8kHz	0.038	01233210

Fig. 16. Modulation waveforms of DG #1.

Fig. 17. Waveforms of DC microgrid system applying PSDM-CL method.

communication is 489mV. This value meets the power quality requirements of the DC microgrid.

Fig. 16 depicts the modulation waveforms of DG #1 when it is sending $dat_k[8]_1$. $x_1(t)$ 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. $v_{ps}(t)$ is the DAC output of $s(t)$, which has been explained in Section II. $\tilde{v}_{PCC\_DG1}$ is the ac component of v_{PCC_DG1} . It can be observed that the carrier frequency used by the synchronization symbol is 3kHz, and the waveforms of $x_1(t)$, $x_4(t)$ and $v_{ps}(t)$ are matched with the theory in Section II.

Fig. 17 demonstrates the operation states of the DC microgrid. It can be observed that V_{PCC_DG1} is around 370V. The ac component $\tilde{v}_{PCC\_DG1}$ has a peak-to-peak amplitude of around 1.2V. The load current of PL #1 I_{o_PL1} is about 5A, which corresponds to 1 kW load. The fluctuation of v_{PCC_DG1} introduced by communication does not exceed 1V. 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 FFT results is distributed

Fig. 18. Demodulation results at PL #1 under $I_{PL1}=1m$.

Fig. 19. Spectrum analysis results of filter output signal.

between 2.5kHz and 8.5kHz. 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 200m. 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

TABLE IV
PARAMETERS OF SUBCARRIERS IN SECTION V.D

Subcarrier	f_{ck}	d_k	$dat_k[8]_2$
x_1	3kHz	0.050	00000003
x_2	4kHz	0.060	21120000
x_3	5kHz	0.070	21120003

Fig. 20. Waveforms of PL #1 voltage and current before and after communication.

Fig. 21. Demodulation results at PL #1 under $I_{PL1}=200m$.

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 600W, 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 600W 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 $dat_k[8]_2$ in Table IV, which proves the feasibility of the proposed method under the circumstances of long transmission distance.

Fig. 22. Influence of power line impedance on communication.

Furtherly, the enlarged waveforms of $\tilde{v}_{PCC\_DG1}$ and $\tilde{v}_{PCC\_PL1}$ during the communication process are illustrated in Fig. 22. The ac amplitude of v_{PCC_PL1} is about 2/5 that of 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. CONCLUSIONS & FUTURE WORKS

This paper 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 is designed, which can be promoted to all power electrical systems applying the OFDM-based PSDM-CL method. A communication rate of 9.6 kbps has been achieved in a 2 kW DC microgrid, which meets the requirements of microgrid applications. Since no additional communication controllers and less communication components are 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 paper can be improved in many aspects. First, advanced techniques used in conventional OFDM, such as equalization and Peak-to-Average-Power-Ratio (PAPR) suppression techniques, can be 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 (ARQ) mechanism can be employed to deal with the communication failure. Third, in long-distance communication applications, additional impedance-match components are required to promote the signal transmission gain of high-frequency subcarriers, which is worth further research.

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