IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 10, 2020, accepted February 21, 2020, date of publication February 27, 2020, date of current version March 12, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2976757

Impedance Detection Based on Ripple Analysis and Current Sharing Control in DC Microgrid

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This work was supported in part by the National Natural Science Foundation of China under Grant 51777120.

ABSTRACT In the operation of DC micro grid, the uniform load distribution is beneficial to the stable operation of the system and prolongs the service life of the system. In order to solve the influence of line impedance on traditional droop control in DC micro-grid, an impedance detection method based on ripple analysis and the structural characteristics of the DC micro-grid system is proposed. The high-frequency harmonic component of microgrid output current and voltage is mainly from the transistor switching frequency. By using the Fourier transform to analyze the high-frequency harmonic component of the voltage and current detected by the converter, the impedance information is obtained, and then the droop control is compensated base on it. In this paper, the compensation method is extended to the application of multiple devices in parallel. This method does not directly operate the system, so it has done no harm to the power quality. Finally, the feasibility of the proposed method in normal working conditions and its effectiveness in the case of communication interruption and load change is verified by RT-LAB hardware in loop experiment.

INDEX TERMS DC micro grid, impedance detection, ripple analysis, current sharing.

I. INTRODUCTION

As a small power generation system, microgrid has self-management function, which can absorb the power generated locally and reduce the pressure on the main grid [1], [2]. The main forms of microgrid include AC microgrid and DC microgrid. With the development of the technology, various DC loads, like electric vehicles increased significantly [3]. At the same time, many new energy power generation technologies generate electricity in the form of direct current. DC microgrid has a great advantage because it does not require repeated AC-DC conversion [4]–[6]. Under the circumstances that the power generation and digestion of new energy sources are urgently needed to be solved, DC microgrids have attracted more and more attention [7].

In the actual operation process, the bus line of the DC microgrid get power from multiple sources. The distance between different power supply to the DC bus line of the microgrid is determined by the actual environment [8]–[14]. Resulting in different line impedance values from source to DC bus line. Those unbalanced line impedance will cause uneven power distribution between converters, affecting the operating life of the converter [15], [16]. It will also cause a certain voltage loss, reduce the DC bus line voltage, and affect the power quality [17].

In order to solve the problem of uneven output current between different converters, a few solutions have been proposed, including distributed control, centralized control and hierarchical control [18]–[21]. The distributed control does not use communication, the converter controls itself according to its own output. So distributed control is difficult to obtain global optimization [22]. Centralized control use communication technology. It can effectively achieve global optimal deployment [23]. Reference [24] analyzes the characteristics of microgrid, and proposes a two-layer nested mesh wireless communication structure based on IoT technology. The IEC61850 interoperability protocol is used to achieve the optimal internal economic dispatching scheme for distributed energy. This method can accurately obtain the working conditions of each converter, and adjust each converter to achieve power sharing. However, the system requires real-time communication, and the two-way communication process increases the uncertainty of the system. It also reduces the stability of system, and the additional communication links improve the risk of system operation. In addition to that, hierarchical control method combines

The associate editor coordinating the review of this manuscript and approving it for publication was Liu Hongchen.

the advantages from these two methods as mentioned. This control method is able to reduce the dependence on communication between converters, while a global optimization control is also achieved. It includes two technical routes. (1), Find out a more reasonable droop coefficient base on the converter output; (2), Measure the line impedance, which cause the uneven current between converters, and building mathematical model to realize the complete current sharing between the converters. Reference [25] is based on the first technical route, it adding virtual impedance to the droop control, and then offsetting the impact of line impedance on load distribution. The system has good current sharing effect. However, the system must be in the initial state of grid connection. Reference [26] introduces a distributed-adaptive droop mechanism for secondary/primary control of dc microgrids which can reduces the complexity of communication topology. this method will get better dynamic response by obtaining line impedance parameters. Reference [27] is based on the second technical route. It using pulse injection to detect the value of line impedance. By modeling the converter and analysis the response of injection pulse from bus line, the line impedance of the circuit is calculated. The droop control coefficient is modified according to the impedance value. This method can effectively get the line impedance and improve the droop control effect. However, the accuracy of this method is low when the equivalent capacitance of the bus line is small, and 5V pulse signal needs to be injected into the bus line. When the line impedance is detected in real time, the voltage quality of the bus line will be affected. Reference [28], the line impedance is measured by intelligent hardware and based on impedance value, a more accurate droop control model is improved. However, additional hardware will increase the cost of the system. At the same time, additional detection links increase the instability of the system. Compared with traditional droop coefficient compensation method, droop control based on line impedance value can achieve better current sharing effect. However, due to the difficulty of impedance detection, its development is limited.

This paper mainly solves the influence of line impedance on the power distribution and voltage quality of multiple converters in parallel in DC microgrid. The method proposed in this paper can realize impedance detection without adding hardware and without direct operation on the input and output of converter. Which make this method more stable and more practical. This method effectively uses the by-product of power electronic converter, high frequency ripple. We use ripple AC characteristics and microgrid topology to calculate the value of the line impedance. Then the accurate droop control and voltage compensation are realized by using the topological characteristics of microgrid. This method can accurately measure the resistance value of the corresponding line impedance of each converter. Therefore, improve the current sharing between each converter, and make up for the influence of line resistance on the voltage quality of the dc bus line. At the same time, this method can detect the line impedance in real time. The line impedance changed due to the change of the environment will be detected and compensate in the droop control. It can reduce the uncertain factors influence of the environment and maintain current sharing effect of the converter. Based on this, the accurate droop control and voltage compensation equation of n-machine parallel connection are derived. Even in the extreme case of complete communication interruption, this method can still provide good current sharing effect. Finally, a hardware in the loop simulation platform based on RT-LAB is established to verify the effectiveness of the proposed method.

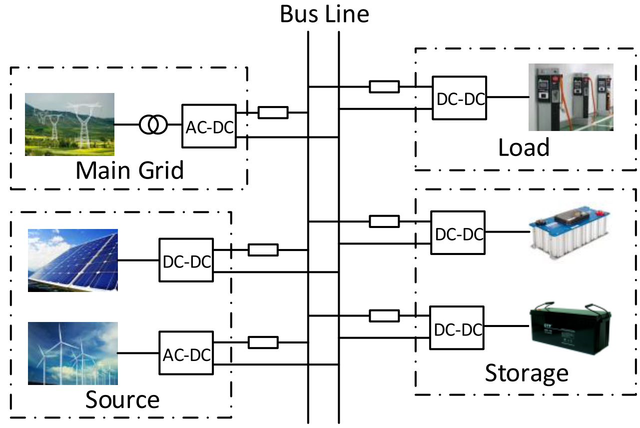

FIGURE 1. Typical structure of DC microgrid.

II. DC MICRO GRID STRUCTURE AND CHARACTER

Figure 1 shows the typical structure of DC microgrid, mainly including wind power, photoelectric, energy storage, power grid and load modules. The wind turbine generates alternating current, which is converted into direct current through AC-DC converter, and then connected to the DC bus line. The photovoltaic array generates direct current. It stabilizes voltage through the DC-DC converter, and connects to the DC bus through the transmission line [29].

The energy storage system contains lithium battery and super capacitor. The energy storage system connects to the DC bus line through bidirectional DC-DC converter. It provides the function of peak clipping and valley filling for the microgrid system, and provides voltage support for the DC bus line [30]. DC microgrid connect with main power grid When the main power grid needs support from microgrid or the internal power of the microgrid is insufficient. The DC microgrid is connected to main power grid through bidirectional DC-AC. DC loads include electric vehicle charging piles, data centers and the like [31], [32]. The energy of each sources is collected on the DC bus line to provide power for various loads.

III. TRADITIONAL DROOP CONTROL AND ITS LIMITATION

The traditional droop control ignores the effect of line impedance on the output current of the converter [32]. This leads to uneven output between converters. It affects converter life and affects bus line voltage quality.

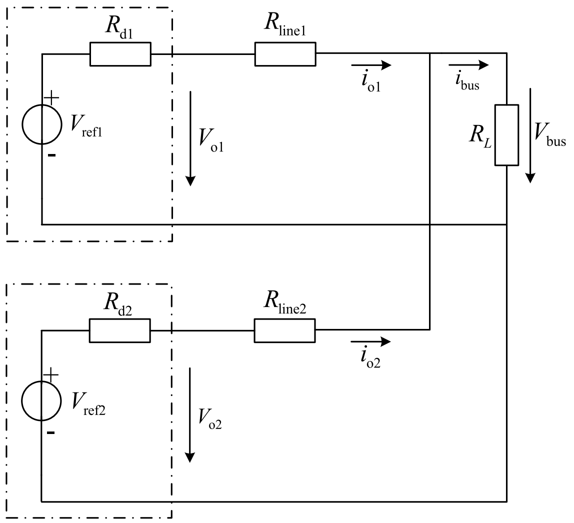

FIGURE 2. Droop control equivalent circuit of two converters connect in parallel.

Figure 2 shows the equivalent circuit when two converters are operated in parallel. $V_{refi}(i = 1, 2)$ is given control target of converter voltage, R_{di} is traditional droop control coefficient, R_{linei} is line impedance corresponding to the converter, R_L is DC microgrid equivalent load, V_{oi} is converter output voltage.

According to Kirchhoff law, the traditional droop control expression and the DC bus voltage equation are

$$V_{oi} = V_{refi} - R_{di} i_{oi} \tag{1}$$

$$V_{bus} = V_{oi} - R_{linei} i_{oi} \tag{2}$$

The value of the traditional droop coefficient is inversely proportional to the capacity of the converter, take two converters for example the express of traditional droop coefficient is

$$R_{d1} = \frac{C_2}{C_1} \tag{3}$$

where R_{d1} is No.1 converter droop coefficient, C_1 is No.1 converter capacity, C_2 is No. 2 converter capacity. According to equation (1) (2), the converter output current ratio is

$$\frac{i_{o1}}{i_{o2}} = \frac{R_{line2} + R_{d2}}{R_{line1} + R_{d1}} \tag{4}$$

According to formula (4), because of the existence of line impedance, the current between different converters are unbalanced. The current difference between two converters caused by line impedance is shown in Figure 3

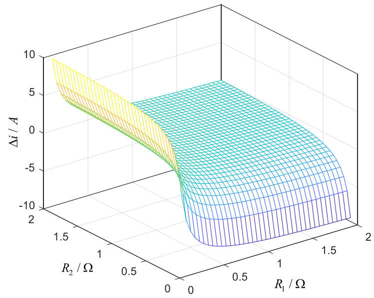

FIGURE 3. The converter current effected by line impedance.

IV. IMPEDANCE DETECTION BASED ON RIPPLE ANALYSIS AND IMPROVEMENT OF DROOP CONTROL

A. IMPEDANCE DETECTION METHOD BASED ON RIPPLE ANALYSIS

Ripple is an irremovable signal produced by power electronic devices in operation. Various forms of electric energy are transformed by power electronic equipment, and the output voltage is inevitably superimposed with some AC components. The main sources of these AC components are switching devices switch quickly. This switching frequency depends on carrier frequency, which is usually very high, generally over 10k [33]. The high frequency ripple of the output voltage of the converter determines that it will not be disturbed by other signals in the working environment, so the information carried by the ripple is relatively stable. By using this characteristic, the collected voltage and current signal can be analyzed by fast Fourier transform through the controller, and the components of voltage and current in each frequency can be obtained. The group with the highest energy in the high-frequency ripple is numerically equal to the PWM carrier triangular wave frequency provided by the controller. This feature of power electronic converter provides a new method for impedance detection. Since the voltage and current signals at each frequency follow the basic Ohm's law, the impedance value of the line impedance can be calculated. The essence of high frequency ripple signal is an AC signal. The output voltage and current of the converter can be changed from time domain to frequency domain by Fourier transform. Fourier transform requires the measured waveform to change periodically. The high frequency harmonic signal of the voltage and current satisfies its working conditions. In practice, the signals collected by sensors are discrete signals, so discrete time Fourier transform is needed [34]. Its expression is

$$X(k) = \sum_{n=0}^{N-1} x(n)\, e^{-j\frac{2\pi}{N}nk} \quad (n, k = 0, 1, \cdots, N-1) \tag{5}$$

where k is spectrum number, n is the time domain signal sequence, N is the length of the time domain signal sequence, $X(k)$ is the spectrum of the discrete time signal $x(n)$. The discrete Fourier transformation algorithm has a large amount of computation. With the reduce by using the method of fast Fourier transformation. The amount of computation can be reduced by using the method of fast Fourier transformation. The periodicity and symmetry of the function can be expressed as

$$\begin{cases} X(k) = X_1(k) + W_N^k X_2(k) \left(0 \le k \le \frac{N}{2} - 1\right) \\ X(k + \frac{N}{2}) = X_1(k) + W_N^k X_2(k) \left(\frac{N}{2} \le k \le N - 1\right) \end{cases} \tag{6}$$

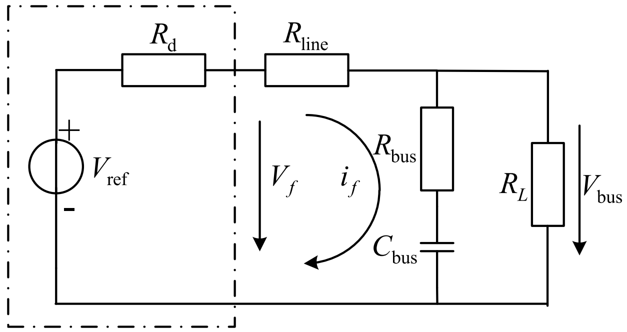

FIGURE 4. The equivalent circuit of single converter.

The controller using equation 6 to execution fast Fourier analysis. It set k as the switching frequency of the switching device. And obtain the high-frequency harmonic values of the converter output voltage and current at the switching frequency.

The topology between a single converter and bus line is shown in the following figure.

V_f is converter output voltage high frequency harmonic, I_f is converter output current high frequency harmonic, R_{bus} is DC bus line impedance, C_{bus} is DC bus line equivalent capacitance.

According to the topology, DC bus equivalent capacitance have characteristics that alternating current can go through it while direct current could not. The high frequency ripple carried by the voltage and current output of the converter which has the alternating current characteristics can be directly returned to the negative electrode through the bus impedance and bus capacitance. At the same time, the high-frequency ripple component of the voltage is at the same frequency as the high-frequency ripple component of the current, and its physical relationship conforms to Ohm's law. Since the bus line length is short, generally only a few tens of meters, its impedance value is close to zero, and it will not affect the desired result, so it can be ignored [35]. The line impedance equation of the transmission line is

$$R_{linei} = \frac{V_{if}}{I_{if}} \tag{7}$$

where V_{if} is $M - th$ high frequency harmonic component of the output voltage of the $i - th$ converter obtained by fast Fourier transform. M is numerically equal to the IGBT switching frequency, which same as PWM carrier frequency provided by the controller. I_{if} is $M - th$ high frequency harmonic component of the output current obtained by fast Fourier transform. R_{linei} is the corresponding line impedance of the $i - th$ converter.

B. ACCURATE DROOP CONTROL BASED ON LINE IMPEDANCE

After obtaining the line impedance value, the droop control equation is further improved. Considering the influence of line impedance, the control target of each converter is changed, and achieve the current sharing effect. Taking the two converters current sharing control as an example, the droop control equation is

$$v_1 = V_{ref1} - i_{o1}R_{line2} \tag{8}$$
$$v_2 = V_{ref2} - i_{o2}R_{line1} \tag{9}$$

In the droop control process, the line impedance is added to the droop coefficient, so that the total equivalent impedance of the droop control becomes larger, resulting in a decrease in the bus voltage and affecting the power supply quality. Therefore, the voltage compensation link is designed. In the control process, the voltage compensation link effectively compensates the droop control coefficient and improves the bus voltage quality without destroying the current sharing effect. Taking the current sharing control of two converters as an example, the voltage compensation equation is

$$\Delta V = \frac{1}{2}\left(i_{o1} + i_{o2}\right)\left(R_{line1} + R_{line2}\right) \tag{10}$$

Combine those two parts, the improved accurate droop control equation is

$$V_i = v_i + \Delta V \tag{11}$$

Taking the two converters current sharing control as an example, the accurate droop control equation is

$$V_1 = V_{ref1} - i_{o1}R_{line2} + \frac{1}{2}\left(i_{o1} + i_{o2}\right)\left(R_{line1} + R_{line2}\right) \tag{12}$$
$$V_2 = V_{ref2} - i_{o2}R_{line1} + \frac{1}{2}\left(i_{o1} + i_{o2}\right)\left(R_{line1} + R_{line2}\right) \tag{13}$$

Under the premise of constant voltage droop control, the shortage of bus voltage is compensated by the energy storage component, and those capacity are wasted. The bus voltage drop caused by the line impedance consumes a portion of the capacity of the energy storage component. The voltage compensation process of accurate droop control compensates for this part of the voltage drop, releasing the capacity of the energy storage component which is used to maintain the bus line voltage, and saving the hardware cost under the same control effect. This part of the capacity can be expressed as

$$\Delta C = I_{bus} * t \tag{14}$$

With the development of renewable energy technologies, the proportion of new energy and distributed power sources in energy has gradually increased. Efficient new energy utilization requires a reasonable power distribution control strategy to maximize its benefits. The number of converters that need to be controlled is huge. Therefore, the precise droop control equation is extended to the case of n converters parallel connection. The accurate droop control equation of n converter connects in parallel is

$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ V_n \end{pmatrix}^T = \begin{pmatrix} V_{ref1} \\ V_{ref2} \\ V_{ref3} \\ \vdots \\ V_{refn} \end{pmatrix}^T - \begin{pmatrix} R_{line1} \\ R_{line2} \\ R_{line3} \\ \vdots \\ R_{linen} \end{pmatrix}^T AB + \begin{pmatrix} \Delta V \\ \Delta V \\ \Delta V \\ \vdots \\ \Delta V \end{pmatrix}^T \tag{15}$$

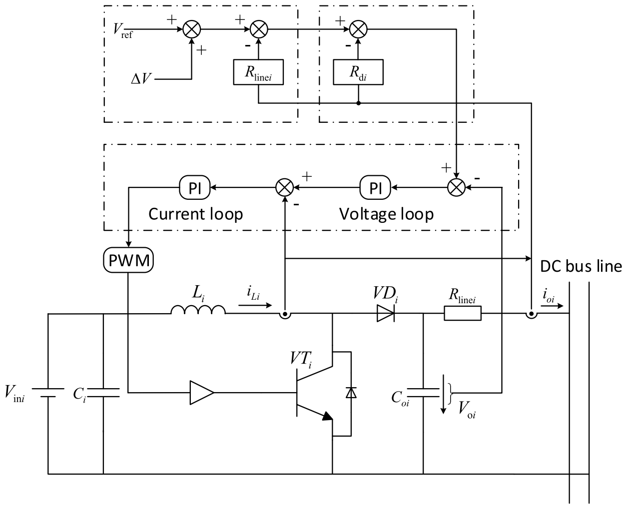

FIGURE 5. System control schematic.

$$A=\begin{pmatrix}0&1&1&\cdots&1\\1&0&1&\cdots&1\\1&1&0&\cdots&1\\\vdots&\vdots&\vdots&\ddots&\vdots\\1&1&1&\cdots&0\end{pmatrix}\quad B=\begin{pmatrix}i_{o1}&0&0&\cdots&0\\0&i_{o2}&0&\cdots&0\\0&0&i_{o3}&\cdots&0\\\vdots&\vdots&\vdots&\ddots&\vdots\\0&0&0&\cdots&i_{on}\end{pmatrix}$$

$$\Delta V=i_{equal}R_{\sum}$$

$$i_{equal}=\frac{1}{n}\left(i_{o1}+i_{o2}+i_{o3}+\cdots+i_{on}\right)$$

$$R_{\sum}=R_{line1}+R_{line2}+R_{line3}+\cdots+R_{linen}$$

R_{linei} is the line impedance value for the $i-th$ converter. The equation can be used to realize the current sharing control and voltage compensation of n converters under the support of weak communication.

The system control schematic is shown as fig 5.

Considering the extreme situation, when each converter is running stably, communication is interrupted, and one of the line impedances is changed by the environment. Those changed line impedance value cannot be transfer to other converters. Taking two converters in parallel as an example, the bus voltage equation is

$$V_{bus}=V_1-i_{o1}R_{line1}=V_2-i_{o2}R_{line2} \tag{16}$$

Bring in accurate droop control equation. Assume that line 1 impedance value changes from R_{line1} to R_{line3}, due to communication interruption, converter 2 still uses R_{line1} as the control parameter. In this case, the converter voltage equation can be expressed as

$$\begin{aligned}V_{bus}&=V_{ref}-i_{o1}R_{line2}+\frac{1}{2}\left(i_{o1}+i_{o2}\right)\left(R_{line3}+R_{line2}\right)\\&\quad-i_{o1}R_{line3}\\&=V_{ref}-i_{o2}R_{line1}+\frac{1}{2}\left(i_{o1}+i_{o2}\right)\left(R_{line1}+R_{line2}\right)\\&\quad-i_{o2}R_{line2}\end{aligned} \tag{17}$$

At this time, the converter is working in the state of current sharing, that is, in the equation

$$i_{o1}=i_{o2}=i_{equal} \tag{18}$$

In the extreme case of communication interruption and line impedance change, the topology still satisfies

$$V_1=V_2=V_{bus} \tag{19}$$

Therefore, under accurate droop control, the bus voltage does not change, and each converter can continue to maintain the current sharing state.

Further we change the dc load, under the condition of communication interruption and line impedance change. The change of load breaks the current sharing state between the converters. The converters current meets the equation.

$$i_{o1}+i_{o2}=i_{bus}=\frac{V_{bus}}{R_L} \tag{20}$$

Combined with equation (19)(20), the current ratio between the two converters is

$$\frac{i_{o1}}{i_{o2}}=\frac{R_{line1}+R_{line2}+\dfrac{\left(R_{line2}+R_L\right)\left(R_{line3}-R_{line1}\right)}{2R_L}}{R_{line2}+R_{line3}} \tag{21}$$

The method can effectively reduce the imbalance of current between converters under the extreme conditions of communication interruption, line impedance change and load change. This conclusion will be verified in experiment in the next part of this paper.

V. EXPERIMENT

In this paper, a hardware in the loop simulation platform based on RT-LAB is built. This platform mainly includes DSPTMS32F28335 as the main control device and RT-LAB equipment used to build the hardware model. The platform is shown in fig 6.

RT-LAB receives PWM control signal from DSP, which is the gate signal of IGBT in boost converter. Each converter outputs voltage and current under the control of corresponding PWM signal. RT-LAB divides the output signal by a gain, so that the signal is in the range of $0\sim16$V. DSP collects the signal through the sensor and multiplies the corresponding gain to get the output voltage and current of each converter in the model, which is the input signal of the controller.

The switching frequency of IGBT is 20kHz. According to Shannon's theorem, the sampling link needs a sampling frequency of more than 40kHz. The controller can provide sampling frequency no more than 6.25MHz. In this experiment, the sampling frequency is set to 1MHz.

A. IMPEDANCE DETECTION EXPERIMENT

The experiment included two parts. First part is change impedance at the 2th and the 4th second. Second part is change inductor value of converter at the 5th second. Because the inductor value of the converter can affect the ripple of the output current, and the current ripple is the cause of

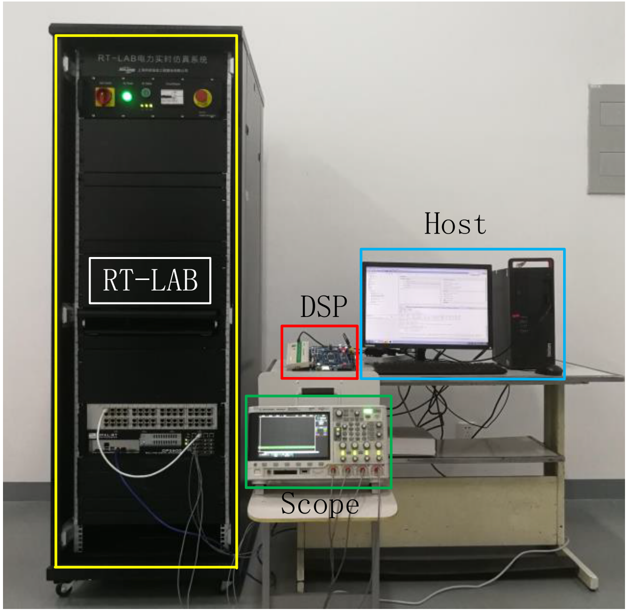

FIGURE 6. Hardware in loop simulation experiment platform.

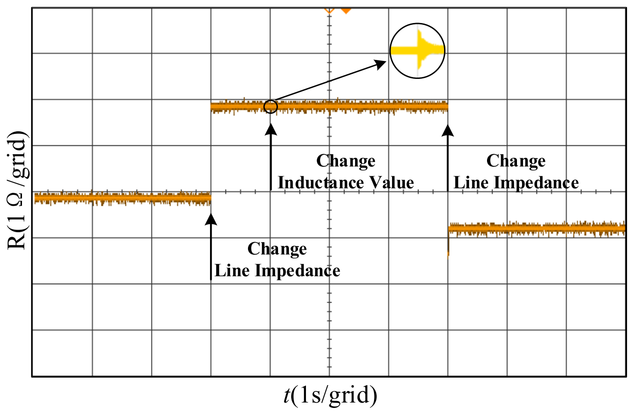

FIGURE 7. The experiment results of impedance detection under different parameters.

the voltage ripple. This experiment is designed to verify the applicability and stability of proposed method under different circuit parameters, and make sure that proposed method can detect line impedance in real time. Figure 7 shows that the impedance analysis method based on ripple analysis can accurately detect the line impedance value and has a good dynamic response. And this method can accurately detect the line impedance under different parameter.

B. ACCURATE DROOP CONTROL AND VOLTAGE COMPENSATION EXPERIMENT CONSIDERING LINE IMPEDANCE

In order to verify the correctness of accurate droop control proposed in this paper, the model of three converters with the same capacity parallel to the same DC bus line is built in RT-LAB model, and the boost circuit is selected for the three converters topology. System parameters are shown in table 1.

TABLE 1. Parameters of system.

Parameter	Unit	Value
bus line voltage	V	400
bus line impedance	Ω	0.0001
bus line capacitance	μF	5000
converter rated power	kW	2
load before change	Ω	40
load after change	Ω	32
line impedance 1	Ω	0.8
line impedance 2	Ω	0.35
line impedance 3	Ω	0.2
converter capacitance	μF	5000
converter inductance	mH	0.8
IGBT frequency	kHz	20
sampling frequency	MHz	1

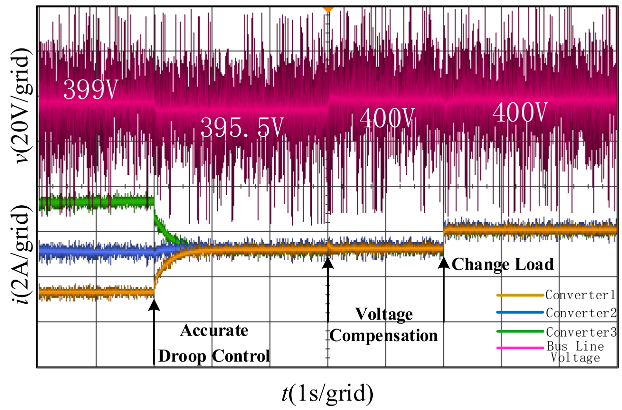

FIGURE 8. Experiment results of accurate droop control.

Figure 8 shows the voltage of DC bus line and the output current of three converters. In the first two seconds, the traditional droop control strategy is implemented. Due to the existence of line impedance, the current of the three converters is unequal. At the 2th second, the controller performs the ripple-based impedance detection method and accurate droop control strategy. The output currents of the three converters reach current sharing state within one second. However, the implementation of this strategy resulted in a 3.5V voltage drop across the line impedance and the bus voltage was further pulled down to 395.5V. The 5th second controller performs the voltage compensation strategy to compensate the bus voltage to 400V, the bus line voltage reaches the control target. The output currents of three converters maintain stable operation after a small range of fluctuations. From the 5th to the 7th second, the system enters a stable operation state. At this time, the DC bus voltage is optimized, and the output currents of the three converters are equalized. In the 7th second, the load is switched, and the current of each converter changes accordingly. The process of change does not affect the current sharing between the converters. The voltage quickly recovers the control target voltage of 400V after a short fall. Changes in load do not affect the current sharing status.

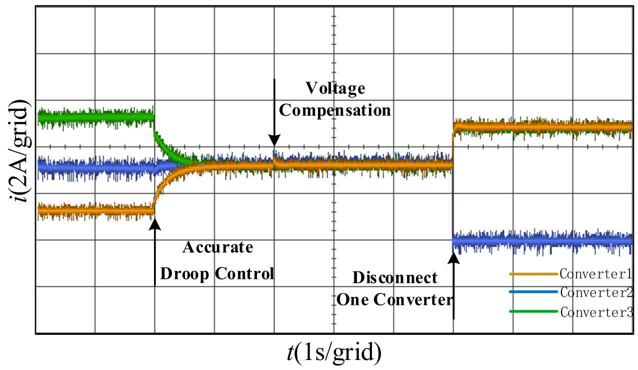

FIGURE 9. Experiment results of disconnect one converter.

TABLE 2. Current of converters.

Work condition	Converter	Current/A
traditional droop control	1	1.37
	2	3.15
	3	5.48
accurate droop control proposed in this paper	1	3.33
	2	3.34
	3	3.33
change load	1	4.16
	2	4.16
	3	4.17
No.2 converter off-line	1	5.00
	2	0.00
	3	5.00

In order to verify the effectiveness of the proposed method when a certain converter is off-line, repeat the above experiment, and cut off the No. 2 converter at the 7th second of the experiment. It can be seen from figure 8 that when one converter is cut off, the remaining two converters can still realize current sharing. The detailed data of the above experiments are shown in Table 2.

In order to verify the working effect of the proposed method under various extreme conditions, this paper designs a set of comparative experiments. The first experiment is control by accurate droop control base on line impedance. The second experiment is control by droop control base on communication according to reference 23. In the first three seconds of the experiment, three converters are working in the current sharing state, and the bus voltage is stable controlled at 400V. In the third second, the communication between converters is stopped. And the line impedance of the converter No. 3 change from 0.2Ω to 0.1Ω, and the variation range is 50%. In the 6th second of the experiment, the DC bus load was changed on the premise that the communication was interrupted and the other converters did not receive the actual line impedance value after the change of the No. 3 line impedance. The results are shown in figure10, table 3 and table 4.

It can be observed from the figure 10(a) that, the interrupt of communication and the change of line impedance does not affect the current sharing effect between the converters under the control of accurate droop control based on line impedance. And after the load change there is an uneven current between the other two converters and No. 3 converter. However, compared with figure 10(b), which the converters are controlled by communication according to reference23. Through quantitative calculation, the imbalance of current between converters under the control of accurate droop control is only 7.59% of the imbalance of current between converters under the control method in reference 23.it can be concluded that: under the influence of superposition of extreme conditions such as communication interruption, line impedance change and DC bus load change, the proposed method can still obtain good current sharing control effect.

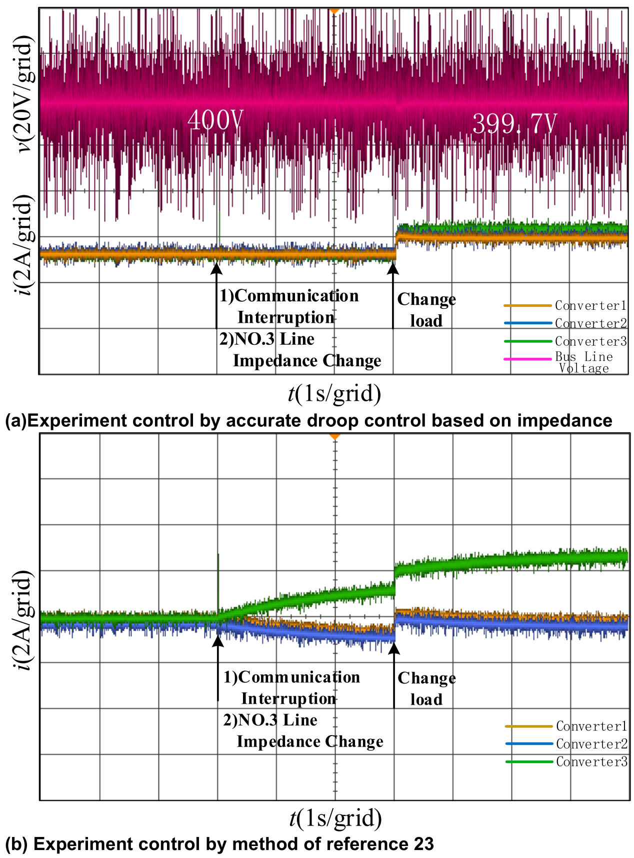

FIGURE 10. Experiment results of communication failure condition and load change.

TABLE 3. Experiment results of accurate droop control under fault conditions.

Work condition	Converter	Current/A
normal	1	3.33
	2	3.34
	3	3.33
communication interrupt line impedance change	1	3.33
	2	3.34
	3	3.33
communication interrupt line impedance change load change	1	3.97
	2	3.97
	3	4.56

TABLE 4. Experiment results of reference23 under fault conditions.

Work condition	Converter	Current/A
normal	1	3.33
	2	3.34
	3	3.33
communication interrupt line impedance change	1	2.72
	2	2.72
	3	4.55
communication interrupt line impedance change load change	1	3.36
	2	3.28
	3	5.85

VI. CONCLUSION

Focus on the line impedance between the converter and the DC bus line, which cause uneven current between the converters in dc microgrid. Through theoretical analysis and experimental verification, the following conclusions are obtained.

1) The PWM carrier frequency provided by the controller determines the on-off frequency of the power device, and an AC ripple signal of this frequency is superimposed on the converter output current. This frequency is determined by the carrier frequency and is not affected by other factors. It can stably carry the line impedance information. Line impedance value can be obtained by analyzing that AC ripple signal.

2) By compensating for the line resistance and the bus voltage drop, accurate current sharing control between the converters can be achieved, the quality of the bus voltage can be improved, and the capacity of the energy storage elements for line voltage drop can be released. The accurate droop control method based on impedance value is extend to the parallel situation of multiple converters and it effectiveness has been verified.

3) The control performance of this method is verified in the case of communication interruption, line impedance change, load sudden change, loss of power supply capacity of a converter. In the case of superposition of the above many adverse factors, the method proposed in this paper can still achieve good current sharing effect.

The equation of this method has great potential in the case of large amount converter connect in parallel. It will provide reference for solving the problem of current balance between converters in the complex power system of multi microgrid parallel connection in the future. However, the equation is too complex and the matrix with large order changes makes it difficult to deal with. This part of the problem will be further analyzed in further research.

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