Transient Modeling Method for Faulty DC Microgrid Considering Control Effect of DC/AC and DC/DC Converters

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ABSTRACT The accurate transient modeling of faulty DC microgrids is the basis of fault detection, fault location and fault isolation. AC/DC and DC/DC converters keep their normal control strategies until the fault is detected. However, in existing researches, the influence of the control effect of converters is normally being ignored in the transient characteristics of DC microgrids. This omission reduces the accuracy of the faulty transient model. Thus, this paper proposes a transient modeling method for faulty DC microgrid considering control effect of different DC/AC and DC/DC converters. Firstly, the transient characteristics of different converters (including voltage source converter, boost circuit, bidirectional chopper circuit and buck circuit) are analyzed. And then, the faulty transient model of ring-type DC microgrid is established. Furthermore, the correctness of proposed modeling method is verified by comparing with the Control-hardware-in-loop (CHIL) test system. The results show that the proposed method can not only improve the accuracy of transient analysis of faulty DC microgrid, but also enhance the calculation efficiency.

INDEX TERMS DC microgrid, faulty transient modeling, control effect, converter.

I. INTRODUCTION

The DC microgrid, which belongs to DC distribution system, is a promising concept in power system [1]. Compared with traditional AC distribution grids, DC microgrids have two unique advantages: 1) There is no concept of “phase” in DC microgrids, which means that the phase synchronization does not need to be considered when AC distributed renewable energies (DERs) are connected [2]; 2) Using DC microgrids to connect with DC devices (such as photovoltaic (PV), energy storage (ES)) can reduce the use of power electronic switches, which makes the distribution systems more efficient and economical [3]. Thus, DC microgrids have been widely used in isolated islands power supply [4], [5], distributed generators (DG) connection [6], [7], asynchronous AC grid interconnection [8], urban power supply [9], electric vehicle [10], [11] and data centers [12], etc. However, DC fault protection has become a great challenge for DC microgrids [13].

Fault detection, fault isolation and fault location are the three basic elements of fault protection. Accurate transient modeling of the faulty DC microgrid is helpful for the selection of the threshold in fault detection [14] and the selection of the parameters of protection devices in fault isolation [15]. Meanwhile, to achieve fault location, the faulty currents obtained by the transient modeling can be used as reference signals to compare with the sampled signals [16]. Therefore, the transient modeling of faulty DC microgrids is the key to provide the analysis basis of fault detection, fault location and fault isolation. The fault characteristic analysis of DC microgrids can be divided into transient analysis for system structures and transient analysis for AC/DC or DC/DC converters.

The system structures of DC microgrids include radial structure, ring structure and mesh structure [17]. The topologies of radial structure are simple. And each line is decoupled. Thus, the fault loops of radial structure can be regarded as resistance-inductance (RL) loops composed of short circuit fault resistance, faulty line resistance and faulty line inductance [18], [19]. In the ring structure, there are two paths between the fault point and any node. Reference [20] disconnects the ring structure from the position, where farthest from the fault point. The simplified ring structure is equivalent to a radial structure centered on the fault point. The complexity
of the mesh structure is the highest, since the lines are coupled with each other. In [21], the matrix expressions of the lines currents in the mesh structure are derived. Furthermore, to make the matrix solvable, the Dijkstra’s path algorithm is used to eliminate the virtual nodes in the matrix. In [15], the Kirchhoff voltage and current equations in the mesh-type DC microgrid are given in the form of difference equations. And the lines currents are iterated automatically. In summary, the transient characteristics of various system structures have been analyzed. Also, accurate transient models have been established.

Voltage source converters (VSCs) and various DC/DC converters are the most commonly used converters in DC microgrids. Firstly, as analyzed in [18]–[22], the transient current being injected from VSCs can be divided into three parts: 1) The discharge current of DC-link capacitor of VSCs; 2) The discharge current provided by the line inductance through the freewheeling diode in VSCs; 3) Short circuit current provided by the AC system through the freewheeling diode in VSCs. Unlike VSCs, there are various DC/DC converter topologies connected with different control objects. The numerical analysis for a DC microgrid with PV was derived in [23]. The results show that the contribution of PV to faults cannot be neglected. Bidirectional chopper circuit is normally used to connect with an ES in DC microgrid [24]. The analysis in [24] shows that the ES contributes to faults when the ground faults occur. The equivalent circuits at different stages of DC/DC converters connected with PV and ES were established in [25]. Moreover, comprehensive comparisons among them have also been investigated. Overall, there have existing researches on the transient modeling of converters in the faulty situation. However, the currents being injected from converters were ignored during the period from fault occurrence to fault detection in previous researches, which reduces the accuracy of fault transient model.

The period from fault occurrence to fault detection is the most important stage on fault transient analysis. And depending on the severity of fault, the time scale of this period ranges from a few milliseconds to tens of milliseconds. For better performance on fault detection, location and isolation, it is necessary to consider the contribution of currents being injected from converters. Since the fault is not detected, the switches in converters are not blocked at this period. And the control systems keep the normal control strategy at this period. To figure out the contribution of fault current being injected from converters, it is necessary to analyze the control effect of converters on the fault transient characteristic.

Under this situation, the transient modeling and analysis of power electronic converters in faulty DC microgrids are accomplished in this paper. The main contributions of this paper can be described as following: 1) The transient responses of power electronic converters (VSC, boost circuit, buck circuit and bidirectional chopper circuit) are modelled and analyzed; 2) A transient modeling method for faulty ring-type DC microgrids is proposed. In addition, the proposed method can be implemented by computer automatically and applied in fault detection, fault location and other situations easily.

The rest of this paper is organized as follows: Section II presents the transient fault analysis problem for DC microgrids; Section III analyzes the transient characteristics of DC/AC converter and DC/DC converter in a faulty ring-type DC microgrid; The numerical analysis of the error between the transient calculation model and the Control-hardware-in-loop (CHIL) test system is completed in Section IV; Section V draws the conclusion.

II. PROBLEM STATEMENT

A. RING-TYPE DC MICROGRID WITH DISTRIBUTED ENERGIES ACCESS

The classic ring-type DC microgrids connected with the distributed energies is taken as the case study in this paper. The schematic of the ring-type DC microgrid is shown in Fig. 1.
This system connects to a variety of AC units and DC units. The AC grid and wind farm (WD) are AC units connected to the DC microgrids by VSCs. While, the PV, battery, super capacitor and DC load are DC units connected to the DC microgrids by various DC/DC converters (including boost circuit, buck circuit and bidirectional chopper circuit).

B. POST-FAULT PROCESS OF THE DC MICROGRID

Fault detection, fault isolation and fault location are the three basic elements of fault protection. And the moments of fault detection, fault isolation, fault location is shown in Fig. 2. Assuming that a fault occurs at time $t_0$. Firstly, the fault will be detected at time $t_1$ by the fault detection devices. Once the fault is detected, the fault isolation devices will be enabled and the switches in converters will be blocked immediately. The fault isolation devices will isolate faulty line at time $t_2$ to ensure the normal operation of other healthy lines. While the fault position will be located at time $t_3$ to ensure the fault be repaired timely. The accurate transient modeling of the DC microgrid during the period from fault occurrence to fault detection is helpful for the selection of the threshold in fault detection and the selection of the parameters of isolation devices. Meanwhile, the faulty currents and nodes voltages obtained by the transient modeling can be used as reference signals compared with the sampled signals in fault location. The use in fault detection and fault location can be found in [26]. While, the use for the selection of parameters of isolation devices. Meanwhile, the use for the selection of the threshold in fault detection and fault location can be found in [27].

III. TRANSIENT ANALYSIS OF FAULTY DC MICROGRID

The transient characteristic of converters is analyzed in this section. Firstly, the transient models of each converter are established. Secondly, to analyze the accuracy of the transient models of converters in a whole DC microgrid, the transient model of each converter is combined to achieve the transient model of the ring-type DC microgrid.

A. MODEL OF AC/DC CONVERTERS IN FAULTY DC MICROGRID

VSC normally works as DC/AC converter to connect with AC grids or WFs in DC microgrids. The topology and control diagram of VSC is shown in Fig. 4. DC-link voltage control is used in VSC, which connects with AC grids, to stabilize DC-link voltage. While active power control is used in VSC, which connects with WFs, to regulate active power. Moreover, the double closed loop control with PI controllers is the commonly control method used in VSC.

The transient analysis of VSC is divided into three stages. The first stage is the establishment of the relationship between output (reference voltage of AC side, which defines as $U_{cd}$ and $U_{cq}$) and input (including DC-link voltage $U_{dc}$, active power $P_{ac}$, reactive power $Q_{ac}$, current of AC side $i_s$ and voltage of AC side $U_s$) in control system. The second stage is the establishment of the relationship between output (modulation current of VSC, which defines as $U_{cd}$ and $U_{cq}$) and input ($U_{cd}^s$ and $U_{cq}^s$) in modulation. The third stage is the establishment of the relationship between output ($P_{ac}$, $Q_{ac}$, $i_s$ and injection current $i_{cov}$) and input ($U_{cd}$ and $U_{cq}$) in hardware circuit.

The first stage: the output $U_{cd}$ and $U_{cq}$ in difference form can be expressed as:

$$
\begin{align*}
U_{cd}^s(k) &= u_{cd1}(k) + u_{cd2}(k) + u_{cd3}(k) \\
U_{cq}^s(k) &= u_{cq1}(k) + u_{cq2}(k) + u_{cq3}(k)
\end{align*}
$$
where $K_{p\alpha}$ and $\tau_{i\alpha}$ are proportional coefficients and integral time constants of PI controller $\alpha$. $R$ stands for $P_{ac}$ in active power control, $R$ stands for $U_{dc}$ in DC-link voltage control, $c$ = $2/T_s$, $T_s$ is sample time, $\omega$ is AC frequency, $L_{ac}$ is inductance of AC lines.

The second stage: since the modulation of the VSC may saturate after fault, the output ($U_{cd}$, $U_{cq}$) of modulation is not equal to input ($U_{cd}^{\ast}$, $U_{cq}^{\ast}$) after $U_c^\ast > U_{dc}/\sqrt{3}$. Thus, in the second stage, the output $U_{cd}$ and $U_{cq}$ in difference form can be expressed as:

$$\begin{align*}
U_{cd}(k) &= \frac{U_{dc}(k)}{\sqrt{3}} \cdot \frac{U_{cd}^{\ast}(k)}{\sqrt{(U_{cd}^{\ast}(k))^2 + (U_{cq}^{\ast}(k))^2}} \\
U_{cq}(k) &= \frac{U_{dc}(k)}{\sqrt{3}} \cdot \frac{U_{cq}^{\ast}(k)}{\sqrt{(U_{cd}^{\ast}(k))^2 + (U_{cq}^{\ast}(k))^2}}
\end{align*}$$

(4)

The third stage: the expressions of $P_{ac}$, $Q_{ac}$, $i_d$, $i_q$ and $i_{cov}$ can be expressed as (5) according to [28]:

$$\begin{align*}
P_{ac}(k+1) &= U_{sd}(k) \cdot i_{sd}(k) \\
Q_{ac}(k+1) &= -U_{sd}(k) \cdot i_{sq}(k) \\
i_{sd}(k+1) &= i_{sd}(k) + \frac{\Delta T}{L_{ac}} \left[\omega L_{ac} i_{sq}(k) + U_{sd}(k) - U_{cd}(k)\right] \\
i_{sq}(k+1) &= i_{sq}(k) + \frac{\Delta T}{L_{ac}} \left[-\omega L_{ac} i_{sd}(k) - U_{cq}(k)\right] \\
i_{cov}(k+1) &= \frac{U_{cd}(k) \cdot i_{sd}(k) + U_{cq}(k) \cdot i_{sq}(k)}{U_{dc}(k)}
\end{align*}$$

(5)

Through the iteration calculation of (1), (4) and (5), the changes of state variables in VSC before fault detection can be calculated.

**B. MODEL OF DC/DC CONVERTERS IN FAULTY DC MICROGRID**

Unlike VSC, there are various topologies of DC/DC converters connected with different objects. This Part analyzes the transient characteristics of PV, ES (battery and super capacitor) and DC load. Meanwhile, the transient characteristics of converters corresponding to the DC units are also analyzed.

1) PHOTOVOLTAICS AND ITS CONVERTERS

Boost circuit is normally worked as DC/DC converter in DC microgrid to connect with PVs. The topologies of boost circuit are shown in Fig. 5. To maximize PV power transmission, Incremental conductance method, which is a popular maximum power point tracking (MPPT) method, is used as the control strategy of boost circuit. The description of incremental conductance method can be found in [29].

The characteristic of PV can be expressed as:

$$i_{pv} = \frac{N_p}{I_0} \cdot i_p - N_p \cdot I_0 \left[ e^{\frac{-q(U_{pv} + i_{pv} \cdot R_s)}{N_s \cdot AKT}} - 1 \right] - \frac{U_{pv} + i_{pv} \cdot R_s}{R_{sh}}$$

(6)

where $I_p$ is the short circuit current of PV, $I_0$ is the reverse saturation current of diode, $R_s$ and $R_{sh}$ are series and parallel internal resistances, $q$ is elementary charge, $A$ is the quality factor of diode, $K$ is Boltzmann constant, $T$ is temperature, $N_s$ and $N_p$ are the number of series and parallel photovoltaic cells.

According to (6), the ratio of the rate of change of current $dI_{pv}$ and voltage $dU_{pv}$ can be expressed as:

$$\frac{dI_{pv}(k+1)}{dU_{pv}(k+1)} = \frac{-\frac{q N_p I_0}{N_s AKT} \cdot e^{\frac{-q(U_{pv}(k)+i_{pv}(k) \cdot R_s)}{N_s AKT}} - 1}{1 + \frac{N_s I_0 R_s}{R_{sh}} + \frac{q N_p I_0 R_s}{N_s AKT} \cdot e^{\frac{-q(U_{pv}(k)+i_{pv}(k) \cdot R_s)}{N_s AKT}}}$$

(7)

The DC-link voltage $U_{dc}$ decreases immediately after fault occurs. Because the transient characteristics of $U_{dc}$ changes rapidly, and the regulation of closed-loop of MTTP has hysteresis, $U_{pv}$ will drop along with $U_{dc}$. According to the $I$-$U$ curve of a single PV cell shown in Fig. 6, the working point of the PV system shifts to the left. Therefore, a constant current source is used to replace the current output of PV. Finally,
be expressed as curve, topology of bidirectional chopper circuit is shown as Fig. 7

The bidirectional chopper circuit is normally worked as 2) ENERGY STORAGE AND ITS CONVERTERS

The bidirectional chopper circuit is normally worked as DC/DC converter to connect with ESs in DC microgrids. The topology of bidirectional chopper circuit is shown as Fig. 7 a).

\[
\begin{align*}
\text{DC-link voltage control is normally used in bidirectional chopper circuit to stabilize DC-link voltage. And the control diagram is shown as Fig. 7 b). Batteries and super capacitors are two complementary ESs. The batteries have high energy density but have slow power regulation speed. In contrast, the super capacitors have fast power regulation speed but have low energy density.} \\
\text{Since the life of batteries decreases as the number of charges and discharges increases, the high frequency component of inputs is generally filtered out in the control system of batteries. Because the short circuit fault is a high frequency power fluctuation, the output of control system for battery is considered unchanged from fault occurrence to fault detection. Thus, the expression of } \text{icov can be expressed as:} \\
\text{where } g_{bt} \text{ is the output of control system, } U_{bt} \text{ is the voltage of battery, } L_{bt} \text{ is the inductance of DC line.} \\
\text{The power regulation speed of super capacitors is fast. Once a fault occurs in DC microgrid, the super capacitor injects power immediately to suppress the dropping of DC-link voltage. The transient analysis of bidirectional chopper circuit for super capacitors is similar to the transient analysis of VSC and also can be divided into three stages.} \\
\text{The first stage is the establishment of the relationship between output } g_{s}^* \text{ and input (} U_{dc} \text{ and } i_{s1} \text{) in control system. The expression of } g_{s}^* \text{ can be expressed as:} \\
g_{s}^*(k) = g_{s1}(k) + g_{s2}(k) \tag{13}
\end{align*}
\]

where

\[
\begin{align*}
g_{s1}(k) &= K_{p5} \cdot [\tau_{5} \cdot \tau_{6} \cdot c^{2} + (\tau_{5} + \tau_{6})c + 1] \\
&\cdot (U_{dc}^* - U_{dc}(k)) \\
&+ 2(2 - \tau_{5} \cdot \tau_{6}^{2}c^{2}) \cdot (U_{dc}^* - U_{dc}(k - 1)) \\
&+ \tau_{5} \cdot \tau_{6}^{2}c^{2} - (\tau_{5} + \tau_{6})c + 1. \tag{14}
g_{s2}(k) &= -K_{p6} \cdot [1 + c^{2}r_{t6} \cdot i_{sc}(k) + 1 - c^{2}r_{t6} \cdot i_{sc}(k - 1)] \\
&+ g_{s2}(k - 1)
\end{align*}
\]

where \(K_{p5} \text{ and } \tau \text{ are proportional coefficients and integral time constants of PI controller } \alpha, \tau = 2/T_{s}, T_{s} \text{ is sample time.} \\
\text{The second stage is the establishment of the relationship between output } g_{s} \text{ and input } g_{s}^* \text{ in modulation. The expression of } g_{s} \text{ can be expressed as:} \\
g_{s}(k) = \begin{cases} 
g_{s\text{max}}, & \text{if } g_{s}^*(k) > g_{s\text{max}} \\
g_{s}^*(k), & \text{if } g_{s\text{max}} \geq g_{s}^*(k) > g_{s\text{min}} \\
g_{s\text{min}}, & \text{if } g_{s}^*(k) \leq g_{s\text{min}} \end{cases} \tag{15}
\end{align*}
\]
The third stage is establishment of the relationship between output \( U_{sc}, i_{sc} \) and input \( g \) in hardware circuit. The expressions of those above variables can be expressed as:

\[
\begin{align*}
U_{sc}(k+1) &= U_{sc}(k) - \frac{\Delta T}{C_{sc}} \cdot i_{sc}(k) \\
(i_{sc} + 1) &= i_{sc}(k) + \frac{\Delta T}{L_{sc}} [U_{sc}(k) - g_{s}(k) \cdot U_{dc}(k)] \\
(i_{co}(k+1) &= g_{s}(k) \cdot i_{sc}(k)
\end{align*}
\]

(16)

The topology and control diagram of buck circuit:

\[\text{FIGURE 8. The topology and control diagram of buck circuit: a) topology of buck circuit, b) control diagram of buck circuit.}\]

3) DC LOAD AND ITS CONVERTERS

Buck circuit is normally worked as DC/DC converter in DC microgrid to connect with DC load. The topology and control diagram of buck circuit is shown in Fig. 8. DC-link voltage control is normally used to stabilize voltage \( U_{ld} \) of DC load.

Similar to the derivation of bidirectional chopper circuit for super capacitors, the transient analysis of buck circuit for DC loads can also be divided into three stages.

The first stage is the establishment of the relationship between output \( g^{*} \) and input \( U_{dc}, i_{ld} \) in control system. The expression of \( g^{*} \) can be expressed as:

\[
g^{*}(k) = g_{11}(k) + g_{12}(k)
\]

(17)

where

\[
\begin{aligned}
g_{11}(k) &= K_{p7} \cdot K_{p8} \cdot \frac{(\tau_{7} + \tau_{8})c^{2}}{\tau_{7} \tau_{8} c^{2}} \cdot (U_{ld}^{*} - U_{ld}(k)) \\
&+ \frac{2 - 2(\tau_{7} + \tau_{8})c^{2}}{\tau_{7} \tau_{8} c^{2}} \cdot (U_{ld}^{*} - U_{ld}(k - 1)) \\
&+ \frac{\tau_{7} \tau_{8} c^{2}}{2} \cdot (\tau_{7} + \tau_{8})c^{2} + 1 \\
(u_{ld}^{*} - U_{ld}(k - 2)) + 2g_{11}(k - 1) - g_{11}(k - 2) \\
g_{12}(k) &= -K_{p8} \cdot \frac{[1 + c\tau_{8}]}{c\tau_{8}} \cdot \frac{i_{ld}(k)}{c\tau_{8}} \cdot \frac{i_{ld}(k - 1)}{c\tau_{8}} + g_{12}(k - 1)
\end{aligned}
\]

(18)

where \( K_{p8}, \tau_{8} \) are proportional coefficients and integral time constants of PI controller \( \alpha, c = 2/T_{s}, T_{s} \) is sample time, \( U_{ld} \) is the voltage of DC load, \( i_{ld} \) is the current of DC load.

The second stage is the establishment of the relationship between output \( g_{l} \) and input \( g_{l}^{*} \) in modulation. The expression of \( g_{l} \) can be expressed as:

\[
g_{l}(k) = \begin{cases} 
   g_{l}^{*}(k), & \text{if } g_{l}^{*}(k) > g_{l}^{*}(k) > g_{l}^{*}(k) \\
   g_{l}^{*}(k), & \text{if } g_{l}^{*}(k) > g_{l}^{*}(k) > g_{l}^{*}(k) \\
   g_{l}^{*}(k), & \text{if } g_{l}^{*}(k) > g_{l}^{*}(k) > g_{l}^{*}(k)
\end{cases}
\]

(19)

The third stage is the establishment of the relationship between output \( U_{ld}, i_{ld} \) and \( i_{co} \) and input \( g_{l} \) in hardware circuit. The expressions of those above variables can be expressed as:

\[
\begin{align*}
U_{ld}(k+1) &= U_{ld}(k) + \frac{\Delta T}{C_{ld}} \cdot [U_{ld}(k)/r_{ld} - i_{ld}(k)] \\
i_{ld}(k+1) &= i_{ld}(k) + \frac{\Delta T}{L_{ld}} [U_{ld}(k) - g_{l}(k) \cdot U_{dc}(k)] \\
i_{co}(k+1) &= g_{l}(k) \cdot i_{ld}(k)
\end{align*}
\]

(20)

C. TRANSIENT ANALYSIS OF FAULTY DC MICROGRID

According to [27], there are only two kinds of variables (nodes voltages and lines currents) in system structures of DC microgrids. And the difference expressions of nodes voltages and lines currents can be expressed as:

\[
\begin{align*}
u_{i}(k+1) &= u_{i}(k) + \frac{\sum_{k=1}^{N} i_{ik}^{(k)}}{C_{i}^{(k)}} \cdot \Delta T \\
i_{j}(k+1) &= i_{j}(k) + \frac{u_{j}(k) - u_{j}(k) - i_{j}(k) \cdot R_{l}}{L_{l}} \cdot \Delta T
\end{align*}
\]

(21)

where \( u_{i} \) is the voltage of node \( i, i_{j} \) is the current of line \( l, i_{ik} \) is the current from node \( i \) to node \( k, \ C_{i} \) is the capacitance of node \( i, R_{l} \) and \( L_{l} \) are the resistance and inductance of line \( l \).

\[\text{FIGURE 9. Faulty line in DC microgrid.}\]

Taking pole-to-pole short circuit fault as an example and supposing a fault occurs on line \( p \). The faulty line is shown in Fig. 9. A faulty node \( n \) and two DC lines \( p_{1}, p_{2} \) are denoted following the occurrence of the fault. The voltage of node \( n \) and currents of lines \( p_{1}, p_{2} \) can be expressed as (22).

The difference expressions of other nodes voltages and lines currents still use (21).

\[
\begin{align*}
u_{n}(k+1) &= (i_{p_{1}}(k) - i_{p_{2}}(k)) \cdot R_{fault} \\
i_{p_{1}}(k+1) &= i_{p_{1}}(k) + \frac{u_{n}(k) - u_{n}(k) - i_{p_{1}}(k) \cdot R_{p_{1}}}{L_{p_{1}}} \cdot \Delta T \\
i_{p_{2}}(k+1) &= i_{p_{2}}(k) + \frac{u_{n}(k) - u_{n}(k) - i_{p_{2}}(k) \cdot R_{p_{2}}}{L_{p_{2}}} \cdot \Delta T
\end{align*}
\]

(22)
where \(u_n, u_m, u_k\) are the voltages of node \(n, m, k\); \(i_{p1}\) and \(i_{p2}\) are the currents of line \(p1\) and \(p2\); \(R_{\text{fault}}\) is the fault resistance; \(R_{p1}, R_{p2}\) and \(L_{p1}, L_{p2}\) are the resistances and inductances of line \(p1\) and \(p2\). \(\Delta T\) is the size of iteration step.

Based on the above analysis, the transient analysis process of a ring-type DC microgrid is iterated by three parts: transient modeling of AC units and their converters; transient modeling of DC units and their converters; and transient modeling of variables in system structures of DC microgrids. Finally, the process of transient analysis of a DC microgrid is shown as Fig. 10.

**FIGURE 10.** Transient analysis process of ring-type DC microgrid.

### IV. NUMERICAL ANALYSIS

The transient calculation models are coded as M-code in Matlab. And the faulty DC microgrid is run in Typhoon 602+ CHIL test system. The accuracy of the transient calculation models is validated by the comparison with the CHIL test system. In addition, to decouple the analysis of each converter’s modeling, the converters are connected to the ideal DC grid respectively. To verify the accuracy of converters’ models in a whole DC microgrid, the converters are connected through a ring-type DC microgrid.

**A. CONTROL-HARDWARE-IN-LOOP TEST SYSTEM**

The experiment platform based on CHIL is shown as Fig. 11. Firstly, the experiment scenarios of DC microgrid are designed in CHIL platform of Typhoon 602+. And the time step of Typhoon 602+ is 1\(\mu\)s. Meanwhile, the control systems of various converters are implemented in TMS320F28335 DSP+ Spartan 6XC6SLX16 FPGA control board and the modulation frequency is 10kHz.

**FIGURE 11.** Experiment platform based on CHIL.

**FIGURE 12.** The Structure of Test System of AC/DC and DC/DC converters.

**B. VALIDATION OF TRANSIENT MODELING OF CONVERTERS**

1) **STRUCTURE AND PARAMETERS OF TEST SYSTEM**

The structure of test system of AC/DC and DC/DC converters are shown as Fig. 12. And the test system can be divided into four parts. Firstly, part 1 is the connected AC or DC units, including AC grid, WF, PV, ES (battery and super capacitor) and DC load. Secondly, part 2 is the converters corresponding to various units: AC grid uses VSC controlled by DC-link voltage control, and the voltage is set as 1000V; WF uses VSC controlled by active power control, and the output power is set as 100kW; PV uses boost circuit controlled by MPPT; ES uses bidirectional chopper circuit controlled by DC-link voltage control, and the voltage is set as 1000V; DC load uses buck circuit controlled by DC-link voltage control, and the voltage of DC load is set as 300V. Thirdly, part 3 includes the DC-link capacitor and DC line. The capacitance of capacitor is set as \(8000 \mu\)F. The length, resistance and inductance of DC line is set as 3km, 0.2Ω and 4mH. Finally, part 4 is a DC voltage source, which is used as an equivalent for the DC microgrid. And the voltage \(U_{\text{sys}}\) is set as 960V.

It is assumed that pole-to-pole faults occur at midpoint of DC line. And to simulate different fault degrees, the fault resistance takes the values of 1\(\mu\)Ω, 1mΩ, 0.1Ω, 0.2Ω and 0.4Ω. And transients characteristics of this test system are analyzed through CHIL test system, calculation model proposed in this paper and calculation model ignoring \(i_{\text{cov}}\). Moreover, the absolute error is used to compare the calculation results and CHIL results.

The errors of \(U_{\text{dc}}\) and \(i_{\text{dc}}\) are related to \(i_{\text{cov}}\). However, the currents \(i_{\text{cov}}\) being injected from converters are ignored in previous researches [18]–[25]. Thus, the modeling method of ignoring the currents \(i_{\text{cov}}\) is used for comparison. And the structure of test system using pervious researches’ modeling method is shown as Fig. 13.
2) VALIDATION OF VSC CONNECTED WITH AC GRID
Taking the fault resistance of 0.1Ω as an example, the waveform of DC-link voltage $U_{dc}$, line current $i_{dc}$ and $i_{cov}$ (filtered through 500Hz) of the test system connected with AC grid are shown as Fig. 14. And the errors of the proposed calculation model and the calculation model ignoring $i_{cov}$ compared with the CHIL test system are shown in Fig. 15. It can be found that $i_{cov}$ obtained by calculation model is similar to $i_{cov}$ obtained by CHIL. The current $i_{cov}$ has the maximum error at the period from 3ms to 8ms. And the maximum error of $i_{dc}$ is less than 10A. Furthermore, since $i_{cov}$ is considered in the calculation of $U_{dc}$ and $i_{dc}$, the maximum errors of $U_{dc}$ and $i_{dc}$ by calculation method are 10.87V and 11.07A. Otherwise, the errors of $U_{dc}$ and $i_{dc}$ will reach 124.98V and 126.57A when $i_{cov}$ is not considered in calculation method.

3) VALIDATION OF VSC CONNECTED WITH WF
Taking the fault resistance of 0.1Ω as an example, the waveform of DC-link voltage $U_{dc}$, line current $i_{dc}$ and $i_{cov}$ (filtered through 500Hz) of the test system connected with WF are shown as Fig. 16. And the errors of the proposed calculation model and the calculation model ignoring $i_{cov}$ compared with the CHIL test system are shown in Fig. 17. It can be found that the trend of $i_{cov}$ calculated by the proposed method is similar to $i_{cov}$ obtained by CHIL. The current $i_{cov}$ has the maximum error at the period from 3ms to 8ms. And the maximum error of $i_{dc}$ is less than 13A. The maximum errors of $U_{dc}$ are less than 18V and the average errors of $U_{dc}$ are less than 6V. The maximum errors of $i_{dc}$ are less than 1.3A, and the average errors of $i_{dc}$ are less than 5A.
to that in CHIL test system. The error of $i_{cov}$ is less than 5A within 7ms from fault occurs. And the maximum error of $i_{cov}$ is less than 15A within 10ms from fault occurs. Furthermore, since $i_{cov}$ is considered in the calculation of $U_{dc}$ and $i_{dc}$, the maximum errors of $U_{dc}$ and $i_{dc}$ are 27.78V and 14.39A. Otherwise, the errors of $U_{dc}$ and $i_{dc}$ will reach 167.98V and 138.91A when $i_{cov}$ is not considered in calculation method.

The more detailed error results under different fault resistances ($1\mu\Omega$, $1m\Omega$, $0.1\Omega$, $0.2\Omega$ and $0.4\Omega$) are shown in Table 2. When $i_{cov}$ is not considered in calculation method, the maximum errors of $U_{dc}$ are greater than 139V and the average errors of $U_{dc}$ are greater than 74V. The maximum errors of $i_{dc}$ are greater than 109A, and the average errors of $i_{dc}$ are greater than 40A. On the contrary, when the transient characteristics of VSC and the corresponding injected current $i_{cov}$ are considered, the maximum errors of $U_{dc}$ are less than 42V, and the average errors of $U_{dc}$ are less than 19V. The maximum errors of $i_{dc}$ are less than 24A, and the average errors of $i_{dc}$ are less than 11A.

| Fault Resistance | Ignored Injected Current | Considering Control System |
|------------------|--------------------------|----------------------------|
| $1\mu\Omega$     | Max 191.07 Min 2.67 Avg 94.40 | Max 41.05 Min 2.67 Avg 18.57 |
| $1m\Omega$       | Max 188.23 Min 3.33 Avg 91.55 | Max 38.10 Min 3.33 Avg 15.74 |
| $0.1\Omega$      | Max 167.98 Min 3.33 Avg 83.83 | Max 27.78 Min 3.33 Avg 12.80 |
| $0.2\Omega$      | Max 151.50 Min 3.33 Avg 74.40 | Max 18.31 Min 2.70 Avg 11.89 |
| $0.4\Omega$      | Max 139.67 Min 3.33 Avg 75.06 | Max 18.92 Min 3.33 Avg 15.06 |

The detailed error results under different fault resistances ($1\mu\Omega$, $1m\Omega$, $0.1\Omega$, $0.2\Omega$ and $0.4\Omega$) are shown in Table 3. When $i_{cov}$ is not considered in calculation method, the maximum errors of $U_{dc}$ are greater than 85V and the average errors of $U_{dc}$ are greater than 50V. The maximum errors of $i_{dc}$ are greater than 88A, and the average errors of $i_{dc}$ are greater than 35A. On the contrary, when the transient characteristics of boost circuit and the corresponding injected current $i_{cov}$ are considered, the maximum errors of $U_{dc}$ are less than 13V and the average errors of $U_{dc}$ are less than 7V. The maximum errors of $i_{dc}$ are less than 24A, and the average errors of $i_{dc}$ are less than 11A.

4) VALIDATION OF BOOST CIRCUIT CONNECTED WITH PV

Taking the fault resistance of 0.1Ω as an example, the waveform of DC-link voltage $U_{dc}$, line current $i_{dc}$ and $i_{cov}$ (filtered through 500Hz) of the test system connected with PV are shown in Fig. 18. And the errors of the proposed calculation model and the calculation model ignoring $i_{cov}$ compared with the CHIL test system are shown in Fig. 19. It can be found that ripples exist in $i_{cov}$ obtained by CHIL, and the frequency is 5kHz. This is because the duty cycle in control system varies by a fixed step size. Since the boost circuit is simplified by mean value model, the ripples are not reflected in the proposed calculation model. Despite the ripples, the error is less than 4A within 10ms after fault occurs. Furthermore, since $i_{cov}$ is considered in the calculation of $U_{dc}$ and $i_{dc}$, the maximum errors of $U_{dc}$ and $i_{dc}$ are 5.40V and 7.62A. Otherwise, the errors of $U_{dc}$ and $i_{dc}$ will reach 85.72V and 101.58A when $i_{cov}$ is not considered in calculation method.

The detailed error results under different fault resistances ($1\mu\Omega$, $1m\Omega$, $0.1\Omega$, $0.2\Omega$ and $0.4\Omega$) are shown in Table 3. When $i_{cov}$ is not considered in calculation method, the maximum errors of $U_{dc}$ are greater than 85V and the average errors of $U_{dc}$ are greater than 50V. The maximum errors of $i_{dc}$ are greater than 88A, and the average errors of $i_{dc}$ are greater than 35A. On the contrary, when the transient characteristics of boost circuit and the corresponding injected current $i_{cov}$ are considered, the maximum errors of $U_{dc}$ are less than 13V and the average errors of $U_{dc}$ are less than 7V. The maximum errors of $i_{dc}$ are less than 24A, and the average errors of $i_{dc}$ are less than 11A.
5) VALIDATION OF BIDIRECTIONAL CHOPPER CIRCUIT CONNECTED WITH ES

Taking the fault resistance of 0.1Ω as an example, the waveform of DC-link voltage $U_{dc}$, line current $i_{dc}$ and $i_{cov}$ (filtered through 500Hz) of the test system connected with battery are shown as Fig. 20. And the errors of the proposed calculation model and the calculation model ignoring $i_{cov}$ compared with the CHIL test system are shown in Fig. 21. Because the life of batteries decreases as the number of charges and discharges increases, the high frequency component of inputs is generally filtered out in the control system of batteries. The short circuit fault is a high frequency power fluctuation. Therefore, in the proposed calculation model, the output of control system for battery is considered unchanged from fault occurrence to fault detection. Although the approximate processing of control system results in a monotonic increase of $i_{cov}$’s error, the error is less than 10A within 10ms after fault occurs. Furthermore, since $i_{cov}$ is considered in the calculation of $U_{dc}$ and $i_{dc}$, the maximum errors of $U_{dc}$ and $i_{dc}$ are 27.72V and 12.53A. Otherwise, the errors of $U_{dc}$ and $i_{dc}$ will reach 135.64V and 126.57A when $i_{cov}$ is not considered in calculation method.

The detailed error results under different fault resistances (1µΩ, 1mΩ, 0.1Ω, 0.2Ω and 0.4Ω) are shown in Table 4. When $i_{cov}$ is not considered in calculation method, the maximum errors of $U_{dc}$ are greater than 132V and the average errors of $U_{dc}$ are greater than 61V. The maximum errors of $i_{dc}$ are greater than 107A, and the average errors of $i_{dc}$ are greater than 40A. On the contrary, when the transient characteristics of bidirectional chopper circuit and the corresponding injected current $i_{cov}$ are considered, the maximum errors of $U_{dc}$ are less than 28V and the average errors of $U_{dc}$ are less than 8V. The maximum errors of $i_{dc}$ are less than 13A, and the average errors of $i_{dc}$ are less than 7A.

### Table 3. The error of $U_{dc}$ and $i_{dc}$ under different fault resistances.

| Fault Resistance | Max | Min | Avg | Max | Min | Avg |
|------------------|-----|-----|-----|-----|-----|-----|
| 1µΩ              | 95.90 | 3.67 | 59.06 | 12.13 | 2.32 | 7.87 |
| 1mΩ              | 91.09 | 2.40 | 55.25 | 8.15 | 0.67 | 4.05 |
| 0.1Ω             | 85.72 | 3.00 | 50.28 | 5.40 | 0.05 | 1.93 |
| 0.2Ω             | 92.09 | 1.00 | 55.22 | 5.73 | 1.00 | 3.25 |
| 0.4Ω             | 92.95 | 2.33 | 55.11 | 6.06 | 0.71 | 2.57 |

### Table 4. The error of $U_{dc}$ and $i_{dc}$ under different fault resistances.

| Fault Resistance | Max | Min | Avg | Max | Min | Avg |
|------------------|-----|-----|-----|-----|-----|-----|
| 1µΩ              | 117.43 | 0 | 41.57 | 13.77 | 0.16 | 6.40 |
| 1mΩ              | 112.87 | 0 | 41.88 | 8.86 | 0 | 2.99 |
| 0.1Ω             | 101.58 | 9.59 | 44.14 | 7.62 | 0.08 | 2.80 |
| 0.2Ω             | 101.46 | 0.18 | 38.65 | 6.83 | 0.03 | 2.52 |
| 0.4Ω             | 88.90 | 0.09 | 35.76 | 6.10 | 0.08 | 2.04 |
error of $i_{cov}$ occurs within 1 ms after fault occurs, and the value is less than 5 A. The error of $i_{cov}$ is reduced and maintained within 2 A from 1 ms to 10 ms. Furthermore, since $i_{cov}$ is considered in the calculation of $U_{dc}$ and $i_{dc}$, the maximum errors of $U_{dc}$ and $i_{dc}$ are 10.36 V and 7.45 A. Otherwise, the errors of $U_{dc}$ and $i_{dc}$ will reach 39.39 V and 40.57 A when $i_{cov}$ is not considered in calculation method.

The detailed error results under different fault resistances ($1 \mu \Omega$, $1 m \Omega$, $0.1 \Omega$, $0.2 \Omega$ and $0.4 \Omega$) are shown in Table 5. When $i_{cov}$ is not considered in calculation method, the maximum errors of $U_{dc}$ are greater than 41 V and the average errors of $U_{dc}$ are greater than 19 V. The maximum errors of $i_{dc}$ are greater than 36 A, and the average errors of $i_{dc}$ are greater than 13 A. On the contrary, when the transient characteristics of bidirectional chopper circuit and the corresponding injected current $i_{cov}$ are considered, the maximum errors of $U_{dc}$ are less than 12 V and the average errors of $U_{dc}$ are less than 4 V. The maximum errors of $i_{dc}$ are less than 8 A, and the average errors of $i_{dc}$ are less than 3 A.

6) VALIDATION OF BUCK CIRCUIT CONNECTED WITH DC LOAD

Taking the fault resistance of $0.1 \Omega$ as an example, the waveform of DC-link voltage $U_{dc}$, line current $i_{dc}$ and $i_{cov}$ (filtered through 500 Hz) of the test system connected with DC load are shown as Fig. 24. And the errors of the proposed calculation model and the calculation model ignoring $i_{cov}$ compared with the CHIL test system are shown in Fig. 25. It can be found that the trend of $i_{cov}$ calculated by the proposed method is similar to that in CHIL test system. The error of $i_{cov}$ is less than 5 A within 8 ms from fault occurs. And the maximum error of $i_{cov}$
is less than 15A within 10ms from fault occurs. Furthermore, since $i_{cov}$ is considered in the calculation of $U_{dc}$ and $i_{dc}$, the maximum errors of $U_{dc}$ and $i_{dc}$ are 7.74V and 14.33A. Otherwise, the errors of $U_{dc}$ and $i_{dc}$ will reach 123.62V and 116.25A when $i_{cov}$ is not considered in calculation method.

The detailed error results under different fault resistances ($1\mu\Omega$, $1\Omega$, $0.1\Omega$, $0.2\Omega$ and $0.4\Omega$) are shown in Table 6. When $i_{cov}$ is not considered in calculation method, the maximum errors of $U_{dc}$ are greater than 111V and the average errors of $U_{dc}$ are greater than 57V. The maximum errors of $i_{dc}$ are greater than 97A, and the average errors of $i_{dc}$ are greater than 34A. On the contrary, when the transient characteristics of buck circuit and the corresponding injected current $i_{cov}$ are considered, the maximum errors of $U_{dc}$ are less than 8V and the average errors of $U_{dc}$ are less than 5V. The maximum errors of $i_{dc}$ are less than 13A, and the average errors of $i_{dc}$ are less than 7A.

### Table 6. The error of $U_{dc}$ and $i_{dc}$ under different fault resistances.

| Fault Resistance | Ignored Injected Current | Considering Control System |
|------------------|--------------------------|---------------------------|
|                  | Max | Min | Avg | Max | Min | Avg |
| $1\mu\Omega$     | 117.75 | 0.43 | 57.04 | 7.68 | 0.01 | 4.79 |
| $1\Omega$        | 113.21 | 0.43 | 58.20 | 7.41 | 0.03 | 5.01 |
| $0.1\Omega$      | 123.62 | 0.44 | 62.78 | 7.74 | 0.20 | 3.10 |
| $0.2\Omega$      | 124.73 | 0.67 | 60.40 | 5.85 | 0.05 | 2.01 |
| $0.4\Omega$      | 118.39 | 0.45 | 58.89 | 6.99 | 0   | 1.58 |

The errors of $U_{dc}$ and $i_{dc}$ are related to $i_{cov}$. However, the currents $i_{cov}$ being injected from converters are ignored in previous researches [18]–[25]. And $i_{cov}$ is influenced by the control of converters. For example, the control target is DC-link voltage when converter connects to SC. To suppress the decrease of the DC-link voltage after fault occurs, the modulation ratio increases rapidly. This causes the drop of $i_{cov}$. Thus, the average errors of $U_{dc}$ and $i_{dc}$ are only 21.04V and 14.80A even if $i_{cov}$ is ignored when converter connects to SC. On the contrary, the control target is selected as active power when converter connects to WF. The control reduces VSC’s AC side voltage $U_{ac}$ to increase active power delivery, and $i_{cov}$ increases continuously after the fault. As a result, the average errors of $U_{dc}$ and $i_{dc}$ reach 83.85V and 47.32A if $i_{cov}$ is ignored when converter connects to WF. Compared with the previous researches which ignores the control effect of converters and injected current $i_{cov}$, the method proposed in this paper can always guarantee the calculation accuracy in the fault transient analysis.

### C. Validation of Transient Modeling of DC Microgrid

1) Parameters of Ring-Type DC Microgrid

The ring-type DC microgrid shown in Fig. 1 is taken as the test system. The parameters and control targets of control systems in converters are the same as those in Part B, Section IV. In addition, both the bidirectional chopper circuits connect with ESs and the VSC connects with AC grid adopt DC-link voltage control. To prevent the conflicts of their control, the control systems in battery and SC only operate when the DC-link voltage is 50V away from 1000V (lower than 950V or higher than 1050V).

The circuit parameters of DC microgrid include DC-link capacitances, lines resistances and inductances. The DC-link capacitances of all converters are set as 8000µF. The resistances and inductances of lines are shown in Table 7. Moreover, the pole-to-pole faults are assumed to occur at midpoint of DC line. And the fault resistance is set as 0.1Ω.

### Table 7. Resistances and inductances of DC lines.

| Line | Resistance | Inductance |
|------|------------|------------|
| 1-2  | 0.20Ω     | 3.00mH     |
| 1-4  | 0.05Ω     | 0.75mH     |
| 2-3  | 0.25Ω     | 3.75mH     |

2) Calculation Accuracy

Taking the fault occurrence at the midpoint of line 3-6 as an example, the waveform of the currents $i_{36, left}$ and $i_{36, right}$ at fault line 3-6 are shown in Fig. 26. In addition, the currents calculated by the proposed method and currents calculated in the case of ignoring $i_{cov}$ are also shown in Fig. 26. And the errors of the proposed calculation model and the calculation model ignoring $i_{cov}$ compared with the CHIL test system are shown in Fig. 27.

It can be found that the trend of $i_{36, left}$ and $i_{36, right}$ calculated by the proposed method are the same as that in CHIL test system. And the maximum errors of $i_{36, left}$ and $i_{36, right}$ are...
can analyze the faulty DC microgrid efficiently. Faster than simulation. This validates the proposed method.

The more detailed error results under different faulty conditions are shown in Table 8. It can be found that, after considering the $i_{\text{conv}}$ that changes with the control systems, the errors of calculated fault currents are reduced. The average error decreased from 76.56A to 6.77A.

TABLE 8. The Error of currents on fault line 3-6.

| Faulty Conditions | Left (unit: A) | Right (unit: A) |
|-------------------|---------------|-----------------|
|                   | Max | Min | Avg | Max | Min | Avg |
| Line 1-2          |     |     |     |     |     |     |
| left              | 102.24 | 0.67 | 79.87 | 12.23 | 0.55 | 7.94 |
| right             | 111.21 | 1.33 | 80.43 | 11.34 | 0.47 | 7.23 |
| Line 1-4          |     |     |     |     |     |     |
| left              | 120.23 | 6.31 | 89.32 | 10.35 | 0.17 | 6.45 |
| right             | 117.34 | 5.32 | 86.49 | 10.43 | 0.34 | 6.42 |
| Line 2-3          |     |     |     |     |     |     |
| left              | 101.43 | 3.48 | 67.67 | 9.88 | 0.08 | 6.52 |
| right             | 100.89 | 4.43 | 68.83 | 9.67 | 0.24 | 6.31 |
| Line 3-6          |     |     |     |     |     |     |
| left              | 97.30 | 5.33 | 74.57 | 12.22 | 0.05 | 7.20 |
| right             | 95.47 | 5.37 | 70.79 | 11.74 | 0.31 | 6.64 |
| Line 4-5          |     |     |     |     |     |     |
| left              | 112.3 | 5.23 | 75.35 | 9.67 | 0.53 | 6.35 |
| right             | 116.3 | 5.64 | 78.34 | 10.23 | 0.56 | 6.95 |
| Line 5-6          |     |     |     |     |     |     |
| left              | 107.8 | 3.56 | 72.42 | 9.45 | 0.23 | 6.77 |
| right             | 104.4 | 4.33 | 74.64 | 9.32 | 0.75 | 6.43 |

3) CALCULATION EFFICIENCY

Referring to the analysis method in [21], the calculation efficiency of the proposed calculation method is analyzed. Using PC with Intel(R) core(TM) i7-8700 CPU @ 3.20 GHz as the experiment platform. The proposed calculation model for the six-terminal ring-type DC microgrid is coded as M-code in Matlab 2018b. The transient characteristics of different converters (including voltage source converter, boost circuit, bidirectional chopper circuit and buck circuit) with different units (including AC grid, wind farm, photovoltaic, energy storage and DC load) are being analyzed. And then the transient model of ring-type DC microgrid, connecting with AC/DC units by different converters, is established. By comparison with the CHIL test system, the transient model proposed in paper improves the transient analysis accuracy significantly and enhances the computational efficiency.

TABLE 9. The time spending under calculation model and simulation.

| Calculation model | Simulation | Speedup factor |
|-------------------|------------|---------------|
| 4.23ms            | 2.45s      | 413.71        |

V. CONCLUSION

Through the analysis in this paper, it is proved that the control effect in converters has contributions on the fault transient characteristic of DC microgrid. Therefore, the influences of the control systems are being considered in the establishment of the transient calculation model in this paper. In detail, the transient characteristics of different converters (including voltage source converter, boost circuit, bidirectional chopper circuit and buck circuit) with different units (including AC grid, wind farm, photovoltaic, energy storage and DC load) are being analyzed. And then the transient model of ring-type DC microgrid, connecting with AC/DC units by different converters, is established. By comparison with the CHIL test system, the transient model proposed in paper improves the transient analysis accuracy significantly and enhances the computational efficiency.

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