Research on fault current limitation and active control for power electronic transformer in direct current grid

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Abstract
Due to the low impedance of DC (Direct Current) power transmission line, short-circuit current has a very high increment speed, which causes problems as difficulty in current limitation method. This paper proposes a new method to realize the current-limiting control of short-circuit current by using active control of power electronic transformer. The method improves the topology of dual active bridge modules that contribute the DC transformer, and installs an IGBT (Insulated Gate Bipolar Transistor) switch in reverse direction on supporting capacitor branch of each module to control the capacitor on or off, which can guarantee the storage energy within the capacitor will not release in initial stage in case of DC short circuit fault happen. Therefore, there is no large inrush current flow out. Furthermore, combined with the requirements of current tracking control during low-voltage ride-through, the transformer output current under short-circuit condition is actively controlled in order to meet the needs of renewable energy power generation equipment. Finally, the simulation and hardware-in-the-loop experiments verify the correctness of this method.

1 | INTRODUCTION

In recent years, DC transmission and distribution networks have attracted the attention of the industry due to their advantages such as large transmission and distribution capacity, small losses, and high-power supply quality [1]. In DC distribution network system, large quantities of power electronic devices are being widely used, and most of them use control algorithm in order to act as voltage source [2], which makes the entire DC power grid show low damping characteristics [3]. This causes much faster current changing rate and wider influence range as well. At present, in most of the cases, there is a large rated supporting capacitor at the output side of the converter. For example, one of the important equipment in DC distribution network is DC power electronic transformer, its circuit topology is mostly based on the double active bridge (DAB) structure [4,5], supporting capacitors are in its both input and output ports [6]. When a short-circuit fault occurs on an external line, the existence of this output supporting capacitor will cause the short-circuit current to be almost uncontrollable in initial stage. The large capacitor discharge current makes it extremely difficult to limit the fault current [7]. In order to solve this problem, the current-limiting inductor method [8] is generally used in the existing projects to limit the short-circuit fault current by connecting a large reactor in series in the DC line. Although it can limit the current rise rate and current peak to a certain extent [9,10], however, with the development of renewable energy power generation, low voltage ride-through function is often required in DC transformers used to connect renewable energy power generation plant and grid connection. At this time, the transformer is required to have the ability to control its output current under various fault conditions. Obviously, it is very difficult to achieve current control by the series-connected inductance method, especially to achieve arbitrary current control during low voltage ride through. It can be seen that before there is no better current control scheme to solve this problem, installing a current-limiting DC reactor refers to a last resort method. Some literature [3,11] pointed out that DC grids must be equipped with DC inductors at both ends of each DC line to protect in cases. The DC grid projects, no matter currently under construction or in planning, also adopt this configuration scheme...
as well [12]. Obviously, a large number of DC inductors need to be used in DC grids, especially in multi-terminal DC grids. This will increase the costs of grid construction and occupy a large construction area. If this problem is solved, it will further promote the development of DC systems.

In DC grids, DC power electronic transformers can be used to connect power grids between different voltage levels or renewable energy distributed generation systems and loads. When connecting the main transmission grid and the user's power grid, if a short-circuit fault occurs on the grid line, the direct-current power electronic transformer can be cut out of operation [13–15] to achieve protection requirement. However, if using a renewable energy grid connection, in the case of a short-circuit fault on an external line, the direct-current transformer cannot be direct removed but required to have a low-voltage ride-through feature [16], that is, the DC transformer cannot be taken out of operation when a short-circuit fault occurs on the line by keeping output a certain amount of current. The magnitude of the current is related to the short-circuit voltage at this time. This is the low-voltage ride-through function that the device must have. On the other hand, due to the protection of the power electronic converter, the converter usually limits its maximum output current [17] to protect the safety of the converter device itself, which has been demonstrated in the current operation. Engineering prototypes have been considered and implemented [18], at mean time played an important role in protecting and transforming the equipment itself [19]. In addition, the maximum output current of the converter is often limited on a fixed value form safety point of view [20], which is usually achieved by blocking the drive pulses of the self-shutdown devices such as IGBT [21], however, this is not enough. Transformer needs to achieve low voltage ride-through function, the fault current can be controlled within a certain range. Furthermore, due to the connection relationship between the supporting capacitor and the external wiring in the DAB circuit's own topology [22], when an external short-circuit fault occurs, due to the discharge of the capacitor, an LC oscillation circuit between the line inductance and the supporting capacitor will cause completely uncontrollable oscillating shock current [23,2]. This phenomenon will longer the controllable transition process to the fault current, which will not give any contribution to the transformer's low-voltage ride-through function [24,25].

Besides the fault current limitation requirements mentioned by low voltage ride through function, from the system protection point of view, to lower the amplitude of short current is also necessary [26,27]. Aiming to cut off the fault transmission or distribution line selectivity, relaying on circuit breaker itself is not enough. The developing speed of fault current is much faster than the selective cut-off speed of the circuit breaker [28,29]. Therefore, in order to reduce the requirements for protection and fault isolation speed, effective DC fault current limiting technology is one of the key techniques for safe and reliable operation of DC system.

This article proposes an improved topology and a short circuit current control method based on DAB circuit module structured DC power electronic transformer [30]. In this topology, electronic switches such as IGBT are installed in reverse direction parallel with the supporting capacitor of each module, together with the rest of the components which constitute a power electronic transformer. By controlling the electronic switch to cut off the supporting capacitor, the previous uncontrollable capacitor discharging current at the initial stage of short-circuit fault is eliminated. At the same time, the active variable structure control method is being implemented. In such a way, the transformer can realize the current limiting follow-up control when processing the low voltage ride-through function. After the short-circuit fault is eliminated, as the electric energy on the supporting capacitor is kept unreleased, there is no need to recharge it. The supporting capacitor is quickly reconnected through the turn on of the IGBT switch, eliminating the slow process of recharging the power electronic transformer and greatly shortening the recovery time from failure. Since the IGBT switch is installed and controlled independently for each module, the current capacity of each switch is affordable by the IGBT, which solve the installation and cost problems caused by using a large DC switch. From the circuit topology and control method given by this article point of view, one hand the output current of the converter is well controlled when a short-circuit fault occurs, and the dynamic process during fault recovery is greatly accelerated. On the other hand, the current-limiting inductor in the DC line can be completely removed. The short-circuit current transition process and the steady-state process are fully controllable, laying a solid foundation for the safe and reliable operation of the multi-terminal DC system.

The structure of this paper is as follows. Section 2 analysis the transformer working process and improvement of circuit topology during DC grid failure; Section 3 describes the control algorithm of output current control method of DAB circuit in detail after supporting capacitor is cut off; Section 4 discuss the quick recovery of power electronics transformer. Section 5 analyses the simulation results. Finally, the conclusion is given in Section 6.

2 WORKING PROCESS ANALYZING AND IMPROVEMENT OF CIRCUIT TOPOLOGY

In the DC distribution network, the grid connection of different voltage levels and the access power of the renewable energy power generation system can be realized by using DC transformers [31]. Figure 1 shows a typical DC distribution network structure diagram.

The DC transformer in the picture can be generally divided into two types according to the attributes of the connected power grid. One type is to connect different voltage levels such as medium voltage AC ± 10 kV to low voltage DC load bus. The other type is the renewable energy power generation system such as photo-voltaic power generation fed into the DC system through a transformer. Considering the convenience,
cost, technology status, and ease of implementation of equipment manufacturers, the current mainstream circuit topology of transformers is basically a DC converter circuit (ISOP) based on DAB module multiple connections. The topology of this family of circuits is highly modular, flexible in combination, and controllable. The efficiency of the entire transformer has now reached 97% (silicon-based devices) or 98% (silicon carbide devices). The DC transformer of this topology has played an important role in the field of DC grids [32,33]. A typical DC transformer with ISOP (input series, output parallel) connection is shown in Figure 2 [34]. The input series mode can withstand high input voltage, and the output in parallel can output large current. Of course, the output voltage at this time is low, which is the voltage of a DAB module [35–37].

It can be seen from the DC transformer structure composed of DAB modules that the DAB module topology circuit has a large-capacity supporting capacitor at both ends, and the transformer formed by series and parallel connection also has the same output and input capacitance characteristics. On the one hand, it plays the role of voltage ripple filtering, and it guarantees the output characteristics of the voltage source of the converter itself [38]. When the transformer is directly connected to an external load, the waveform of its DAB converter, supporting capacitor, and transformer output current in one DAB unit can be seen in Figure 3. The expression of $i_{\text{boul}}, i_{\text{cap}}, i_{\text{out}}$ can be referred in Figure 2.

Figure 3 shows the working condition of a DC transformer with a voltage source when supplying power to a load. Due to

**FIGURE 1** Structure diagram of DC distribution network including renewable energy power generation system

**FIGURE 2** ISOP DC transformer structure diagram
the voltage source output property, the output current of the transformer will be adjusted according to the power required by the load. At this time, due to the relatively stable state, the current of the system will also remain constant, and the current will remain basically the same; however, when a short-circuit fault occurs on the external circuit of the transformer, due to the small line impedance and the release of the supporting capacitor energy in the transformer, a large line current will be generated, which will cause serious damage to equipment and circuits. In order to prevent this kind of accident, the method in the existing project is to connect a current-limiting inductor together with DC circuit breaker at the transformer output to protect power line and equipment. The working principle is to limit the rise rate of the short-circuit current when the short-circuit fault occurs through the current-limiting inductor. Providing a buffer time for the circuit breaker to cut off the circuit and achieve the purpose of line protection. The current-limiting protection scheme in this way is sufficient. However, more and more renewable energy power generation systems are currently connected to the DC grid, and from the perspective of improving the reliability of power supply point of consideration, equipment needs to have the function of providing low voltage ride-through. At this time, the inductor with circuit breaker scheme is obviously cannot be satisfied. Relying on a large inductor can certainly limit the current to a certain range, but if the circuit breaker does not cut off the circuit, the system may have resonance between the line inductive reactance and the supporting capacitor. An oscillation waveform between a line inductance and a supporting capacitor is shown in Figure 4. At this time, the transformer cannot achieve the current-limiting current control required for low voltage ride-through.

From the above analysis, it can be seen that the reasonable treatment of DAB’s supporting capacitor energy is critical to ensuring equipment safety and current control. In the current DAB topology, when the short-circuit fault occurs, the energy on the capacitor is uncontrollable, which will cause the discharge current waveform to be uncontrollable at the initial stage. If the supporting capacitor can be cut off from the circuit when the short-circuit current occurs, the energy on the capacitor will not be released, which will accelerate the controllable realization of the transformer output current, and realize the low voltage of the device by means of the current loop control inside the transformer.

Facing to the problem of fault current control, besides using series-connected inductor to the output, improving the topology of transformer itself has become the mainstream solution in the today’s industry field. One of the easiest solutions is to add a half bridge following to the output of each DAB module (see Figure 5). The dashed circle indicates the current-limiting half bridge structure. In principle, it is no problem to realize the function, however, there are two weak points need to be solved. First is the low utilization of the semiconductor switches, since only lower side switch (S10) participates the activity of fault current limitation. Second is the high power conducting losses during normal operation process. Output currents will flow through the normally-on IGBT (S9), the amplitude of the current is relatively high which surely will cause higher conducting losses and have negative affect the total efficiency.

For solving the problems mentioned above, a detachable DAB circuit based on the concept of a power electronic switch control supporting capacitor is shown in Figure 6. In Figure 6, Qcap is a power electronic switch installed in reverse direction to control the supporting capacitor to be detachable. When the transformer works normally, Qcap is turned on. When the supporting capacitor Cout needs to be
**FIGURE 4** The waveform of output current, voltage, supporting capacitor current in the double active bridge module of the transformer when the external line is shorted.

**FIGURE 5** Double active bridge structure with half bridge fault current limitation module.

**FIGURE 6** The double active bridge module circuit with supporting capacitor that can be turned off by power electronic switch.
charged, the current flows from the positive bus bar through the diode in the $Q_{\text{cap}}$ body, into the supporting capacitor $C_{\text{out}}$. When the supporting capacitor $C_{\text{out}}$ needs to be discharged, the current flows from the supporting capacitor through the IGBT to positive bus. If a short-circuit fault occurs on an external line, a cut-off control instruction is quickly given to the IGBT, and the IGBT is turned off. After the IGBT is turned off, the supporting capacitor $C_{\text{out}}$ will not be able to release the energy on the capacitor to the external short-circuit line. The peak value of the short-circuit current and its uncontrollable time will be greatly reduced. With the help of the controllable components inside the DAB circuit, its output current can be controlled completely. However, it should be noted that the output characteristics of the DAB circuit will change before and after the supporting capacitor is cut off, from the original voltage source type to the current source type. At the same time, the energy on the supporting capacitor will be stored, so that the DAB can resume normal operation without recharging after fault recovery.

There are several advantages to using an IGBT in each DAB module as a switch in its supporting capacitor branch. First, the operating time of the IGBT is very fast, which can fully meet the time required to turn off the capacitor discharge branch; Secondly, because this switch is provided in each DAB module, the IGBT current rating flowing through the switch is dispersed, and the current flowing through each IGBT is not large. This point can also be better understood by observing the working condition of the supporting capacitor branch current waveform in Figure 6, and installing an IGBT in the production process is more convenient than installing a circuit breaker in the entire circuit, and the price is much lower.

3 | OUTPUT CURRENT CONTROL METHOD OF DOUBLE ACTIVE BRIDGE CIRCUIT AFTER SUPPORTING CAPACITOR CUT OFF

3.1 | Changes in double active bridge circuit topology after short circuit fault

As the fundamental unit which construct the DC transformer, each DAB module an output supporting capacitor cut-off switch is added. In this way, the cut-off current can be greatly reduced to $1/N$ as the total output current ($N$ is total number of parallel-connected DAB module). Under this circumstance, power electronic switches are possible to be implemented instead of large volume DC breakers. In Figure 6, a power electronic switch $Q_{\text{cap}}$ that controls the switching of the supporting capacitor $C_{\text{out}}$ is installed in the DAB circuit. When a short-circuit fault occurs on the transmission line, the control system issues a command to lock the $Q_{\text{cap}}$ switch, so that the supporting capacitor $C_{\text{out}}$ in the original DAB circuit will be stripped. At this time, the topology of the circuit will change as follows: the circuit on the right side of the high-frequency transformer in the DAB will become a fully controlled rectifier bridge and supply to the resistive load. The circuit will no longer show the voltage supported by the large capacitor source form, but instead changes to a current source mode. For DAB circuits, the variables that can be controlled are 4 IGBTs in the primary-side inverter bridge, 4 IGBTs in the secondary-side rectifier bridge, and the voltage phase difference between the primary and secondary sides of the high-frequency transformer. These quantities are controllable. It illustrates the flexibility of DAB structure control, but on the other hand, it also brings the complexity of control. According to the analysis of the working condition of the line short circuit, it can be known that when the line has a short-circuit fault, its impedance value be very small. To achieve the current control during the short circuit, the output voltage of the secondary side rectifier bridge of the DAB should not be high. For a rectifier bridge composed of fully controlled devices, the minimum output voltage is the rectified voltage in its natural rectified state.

In order to simplify the control, when the DAB circuit works in a short-circuit fault state, all 4 IGBT drives of the rectifier bridge on the secondary side can be completely blocked, and the rectifier bridge on the secondary side becomes a diode rectifier bridge. The output current of the DAB is fully controlled by the primary-side inverter bridge. At this time, there are two working states for the secondary side rectifier bridge. One is the high-frequency transformer has a positive or negative output, the circuit appears as a single-phase diode externally connected to the L-R rectifier circuit. The second is that the transformer has no output. It appears as an L-R freewheeling circuit. The output characteristics of the entire circuit at this time have been shown as a rectifier bridge with L-R load current control mode, which is completely different from the voltage source during the DAB normal operation. Figure 7 shows the schematic diagrams of current flow at these different working moments.

In summary, after the supporting capacitor is removed, the output circuit of DAB can directly adjust the sub-side output voltage of the high-frequency transformer through the out-of-phase shift control of the DAB primary-side inverter bridge, and then control the output current of the entire DAB circuit.

3.2 | Equivalent model of double active bridge circuit after removing supporting capacitor

From the previous analysis, it can be seen that, taking the $Q_{\text{cap}}$ operating moment of the supporting capacitor switching as the boundary, the external characteristics of the DAB circuit have changed. From the voltage source before the $Q_{\text{cap}}$ operation has been changed into the current source mode. The following two points need to be pointed out.

1. After the DAB circuit structure is changed, there is no supporting capacitor in the circuit. In order to achieve the low voltage ride through characteristics, the task of the
DAB circuit at this time is to control its output current. The control of the output current of the entire DAB circuit can be completed through the phase shift control of the primary-side inverter bridge;  

2. It can be found that after removing the supporting capacitor, if you consider various non-linear situations such as intermittent and continuous current, there will be many control methods for DAB output current control. To simplify the analysis process, this article only selects the case where the DAB output current is completely continuous, without considering the current discontinuity or critical state. The analysis of the current interruption or critical state will be specifically studied in a subsequent article.

Assume that $I_{\text{short}}$ is the equivalent total inductance of the short-circuit location and the DAB output side transmission line, and $Z_{\text{short}}$ is the equivalent total impedance of different types of short-circuit faults. Because the equivalent inductance and impedance inside the DAB circuit are small, $I_{\text{short}}$ and $Z_{\text{short}}$ will be mainly determined by the short-circuit location. The distance to the transformer and the short-circuits impedance are determined. Considering the line load in the circuit of Figure 7, the equivalent circuit is shown in Figure 8.

The high-frequency transformer in Figure 8 is represented as follows: $L_1$ and $L_2$ are the primary and secondary inductance, $L_m$ is the magnetizing inductance, and $C_m$ is the interlayer capacitance. The above parameters are converted to the primary side; $i_P$ is the value converted from the secondary side current.
of the isolation transformer to the primary side. On the basis of Figure 8, using the T-type equivalent circuit model of the transformer, an L-C-T type DAB equivalent circuit model as shown in Figure 9 can be obtained.

Considering the DAB control method described above and the line parameters after a short circuit, the DAB control at this time can be considered as a single-phase high-frequency inverter circuit with variable parameters of the resistance load. As the short-circuit location is unknown beforehand, it can be seen that the load parameters $L_{\text{line}}$ and $Z_{\text{load}}$ are also unknown parameters during current control. Different short-circuit distances and different types of short-circuit faults can cause $I_{\text{short}}$ and $Z_{\text{short}}$ to change several times, also if to give the same value of output current, the primary-side rectifier bridge control parameter-phase shift duty cycle $d$ will also be very different at different short-circuit distances. Figure 10 shows the waveform comparison of two different short-circuit distances when the same output current is required. It can be seen that for the DAB circuit after the supporting capacitor is cut off, the current control will face the problem of uncertain load parameters, and the design of the current controller will become more complicated in its type and parameters.

3.3 Research on current limiting control methods

For the equivalent circuit using the primary-side inverter bridge control shown in Figure 9, the T-type impedance equivalent circuit of Figure 11 may be used.

The working frequency of a DAB circuit is usually several thousand Hz to several tens of thousands Hz. The effect of the equivalent resistance in the transformer winding is much smaller than the effect of the equivalent inductance, and due to the increase of the operating frequency. The effects of capacitive effects should also be considered as the interlayer capacitance and parasitic in the high frequency transformer. Therefore, the parameters in the equivalent circuit of Figure 10 are shown in Equation (1):

$$
\begin{align*}
Z_0 &= s(L_{\text{m}} + L_1) + \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + s^{1}L_{\text{m}}C_{\text{m}} + 1} + \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + s^{1}L_{\text{m}}C_{\text{m}} + 1} \\
Z_{\text{m}} &= \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + 1} + \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + 1}, \\
Z_{\text{n}} &= \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + 1} + \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + 1} + \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + 1} + \frac{sL_{\text{m}}I_{\text{m}}}{s^{2}L_{\text{m}}C_{\text{m}} + 1}.
\end{align*}
$$

FIGURE 9 L-C-T double active bridge equivalent circuit model

FIGURE 10 Waveform comparison of different short-circuit distances when the same output current is required. Short circuit fault occurrence at far distance, (b) short circuit fault occurrence at close distance

FIGURE 11 T-type impedance equivalent circuit
Here $\omega_{m}$ is the equivalent inductance of the primary-side inverter, $\omega_{i}$ is the equivalent inductance of the high-frequency transformer, $\omega_{m}$ is its excitation inductance, and $\omega_{i}$ is its equivalent capacitive reactance, $Z_{S}$ is its equivalent reactance after the impedance of the secondary side is converted to the primary side. After calculation, the relationship between the input $i_{1}$ and the output $i_{2}$ in Figure 10 is given by Equation (2):

$$
U_{1} = \frac{1}{z_{m}} \left[ (\zeta_{1} \zeta_{2} + \zeta_{1} \zeta_{m} + \zeta_{2} \zeta_{m}) I_{2} + (\zeta_{1} + \zeta_{m}) U_{2} \right].
$$

In the case of a short-circuit fault, the voltage on the secondary winding of the transformer is only the line impedance between the short-circuit point and the transformer and the voltage drop caused by the short-circuit impedance at the short-circuit point when the short-circuit occurs, which can be expressed by the following formulas:

$$
U_{2} = (\zeta_{\text{line}} + \zeta_{\text{short}}) I_{2}
$$

$$
U_{2}' = N U_{2}
$$

Assume that the ratio of the primary and secondary sides of the high-frequency transformer is $N$: 1. The relationship between the entire DC transformer output current $i_{2}$ and the input voltage $u_{1}$ is:

$$
I_{2} = \frac{N \zeta_{m} U_{1}}{\zeta_{1} \zeta_{2} + \zeta_{1} \zeta_{m} + \zeta_{2} \zeta_{m} + N(\zeta_{1} + \zeta_{m})(\zeta_{\text{line}} + \zeta_{\text{short}})}.
$$

Substituting Equation (1) into Equation (5), the relationship between the output control voltage of the primary-side inverter and the output current of the DC transformer when a short circuit occurs can be obtained.

The following analysis is performed with a specific example. The primary side excitation inductance of a high-frequency transformer is $L_{m} = 167 \mu$H, the primary side leakage inductance $L_{1} = 22.2 \mu$H, the secondary side leakage inductance $L_{2} = 12.3 \mu$H, and the primary side layer of the transformer is measured at 10 kHz. The inter-capacitance $C_{m} = 0.032 \mu$F, the inverter equivalent reactance $L_{i} = 2.06 \mu$H, and the transformer transformation ratio $N = 1.3$. The above parameters are substituted into Equation (1), and the Bode plot is used for stability analysis of the target transfer function Equation (5). Because the line distance and the type of short-circuit fault are unknown, the line impedance and short-circuit impedance are changed in a wide range on the load side in the model parameters. The Bode plot of this system is shown in Figure 12.

It can be seen from Figure 12 that when the amplitude-frequency characteristics of the controlled object cross the zero-decibel line, its phase-frequency characteristics are basically around $-90^\circ$, and the farther the short-circuit fault occurs, the greater the short-circuit impedance, and the system shown the better the stability. However, it should also be noted that there are instability factors in the high frequency bands. The system will generate resonance when it is disturbed, and there are more than 3 resonance points in these frequency bands. The vicinity of these points is also its unstable area. The closer the fault occurs, the easier it is for the system to enter these resonance points. Therefore, it should be pay attention to these issues when designing the controller. Furthermore, because the location and form of the short circuit are unknown beforehand, although the entire current control system exhibits a second-order closed-loop control characteristic in the low frequency band, the uncertainty of the two parameters $Z_{\text{line}}$ and $Z_{\text{short}}$ will affect the dynamic process and stability of the output current. The steady state current accuracy has a greater impact. In the extreme case, these two parameters can be close to 0, or they may have a larger value. Especially when the fault distance is short, the impedance parameter of the system is small, and the current in the DC grid rises quickly. If the current limiting control of the power electronic transformer is still controlled by ordinary methods, it is difficult to ensure the accuracy of current tracking and the stability of the system. It is difficult to meet the current limiting and low voltage ride-through requirements. Therefore, if it wants to limit the output current $i_{2}$, the phase shift duty cycle $d$ of the inverter bridge that controls the output voltage should be limited. In order to solve this problem, this paper uses a current-minimum hill-climbing adaptive control method to limit and accurately control the current during the fault period.

The basic idea is as follows: When the control system finds that the system has a short-circuit current fault, the DAB primary-side inverter bridge is switched to the phase-shift control mode, and the phase-shift duty cycle $d$ is assigned to the minimum value. Then start to measure the output current $i_{2}$, and wait for the current $i_{2}$ to drop to the minimum value. The current is no longer reduced after waiting, the current value at this time is used as the starting point of the hill-climbing control algorithm, and then the integral principle effect is used to gradually increase the reference current value to the required current limit value. For a detailed schematic diagram of the implementation method, please refer to Figure 13. On the other hand, adaptive control algorithm is used to implement the current control loop controller at this time. Compared with general classical control methods, adaptive control is more suitable for controlling the changes of system object parameters after a short circuit. The control quality has a small known dependence on the parameters of the controlled object, which guarantees the current limiting and output current control accuracy of the DC transformer.

## 4 QUICK RECOVERY OF POWER ELECTRONICS TRANSFORMER

According to the control requirements of low-voltage ride-through, after the short-circuit fault of the external line is eliminated, the power electronic equipment in the line should resume operation in the shortest time. In the DAB circuit designed in this paper, since the supporting capacitor is separated from the
FIGURE 12  System bode diagram for different short-circuit locations and faults
the DAB circuit will switch from the current source to the voltage source control mode again seamlessly. The relevant experimental results will be given in Section 5.

5 | EXPERIMENTAL RESULTS

In order to verify the correctness of the circuit topology and control method mentioned in the previous article, a hardware-in-the-loop experimental system based on the dSPACE and Plecs-RT box platforms is constructed in this paper. The above circuit topology and control method are fully verified in practice. The experimental platform is shown in Figure 14. The current-limiting control experiment mainly includes three parts.

5.1 | Experimental waveforms of current limiting using output inductor

Using hardware in the loop experiment setup, the chapter shows the results of waveforms using serial connected inductors with different values. The energy stored within the supporting capacitor will release instantaneously, cause dramatic large inrush current to the output side. Waveforms shown in Figure 15 describe the results using different values of inductor. Inductor with small inductance can hardly limit the inrush current which produce large peak at the first time (see in Figure 15(a)). This peak current will not be limited only if adding an enormous...
inductance inductor, which can refer to Figure 15(b). However, an LC oscillation is generated between output inductor and supporting capacitor, in this case, the fault current control cannot realize low voltage ride through.

5.2 Experimental waveforms of current limiting using current tracking method

In order to verify the correctness and effectiveness of the current tracking control method described in this paper, a verification experiment was performed on experimental platform based on Figure 14. During the experiment, based on the MATLAB simulation results, the control algorithm described in the article was implemented in dSPACE, then converted into PWM waves and output to the DAB converter which module and circuit simulated by Plecs RT-box. Figure 16 indicates the waveforms based on different reference current based on current tracking control method. Figure 16(a). shows the result of output current \( i_{\text{out}} \) which is bigger than the value before fault happen and Figure 16(b). outputs the value smaller.

It can be seen from Figure 14 that when a short-circuit fault occurs, the supporting capacitor is cut off by the IGBT switch, so the voltage on the supporting capacitor is unchanged before and after the fault occurs. During the short-circuit fault period, the output voltage \( u_{\text{out}} \) is close to 0, and the output current \( i_{\text{out}} \) stabilizes according to the set current under the condition that the DAB is controlled. There is no current uncontrollable phenomenon in Figure 15. Owing to the fact that hill climbing adaptive control method limit the amplitude of inrush current, the effectiveness of the control method mentioned in this paper can be proved, and the possibility of transformer’s low voltage ride through function is realized.

5.3 Experimental waveforms of fast fault recovery control

Figure 17 shows the voltage and current operating waveforms when the DAB circuit resumes normal power control after the short-circuit fault is removed. Figure 17(a) gives the result of output current after fault recovery is close to the current before fault clarify. Figure 17(b). shows the situation of the current which is smaller than before. It can be seen from below two figures, since the voltage on the supporting capacitor does not need to be recharged, after the IGBT switch is turned on again, the DAB circuit is restored to the control mode of the voltage source. The switching recovery time of the entire circuit becomes very short, which can be clearly noticed if zoom in the time scale (see Figure 17(b)). The whole process can be done...
DOUBLE ACTIVE BRIDGE CIRCUIT RESUMES WAVEFORM AFTER SHORT CIRCUIT IS REMOVED. (A) RECOVERY OUTPUT CURRENT CLOSE TO THE VALUE DURING FAULT HAPPEN, (B) RECOVERY OUTPUT CURRENT SMALLER THAN THE VALUE DURING FAULT HAPPEN WITHIN 2MS WHICH SPEEDS UP BACK TO THE NORMAL OPERATION OF THE ENTIRE DC POWER SUPPLY SYSTEM.

6 | CONCLUSION

There will be a large amplitude inrush current occur when short circuit happen in DC grid because of its low impedance characteristic. Because the appearance of supporting capacitor in voltage source type DC/DC electronic transformer, the peak amplitude and maintaining time of the inrush current will further increase. An effective solution to solve the problem mentioned above is raised by this paper with method of introducing the removable supporting capacitor. The following conclusions are drawn from the research in this article:

1. During a DC Grid short-circuit fault, suppressing the release of energy in the supporting capacitor in the DAB module can effectively reduce the peak short-circuit current and the uncontrollable time of the short-circuit current. The installation of power electronic switches can achieve effective control of the energy release of the supporting capacitor;
2. Requirement of low voltage ride through function can be satisfied by controlling the DAB modules in electronic transformer respectively. It should pay attention to the switching process from voltage control to current control. A proper control method is vital important to realize the current tracking. Attention should also be paid to dynamic characteristics control problems and stability problems caused by the unknown parameters of the controlled object of the current loop.

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REFERENCES

1. Justo, J.J., et al.: AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renewable Sustainable Energy Rev. 24, 387–405 (2013)
2. Baran, M.E., Mahajan, N.R.: DC distribution for industrial systems: opportunities and challenges. IEEE Trans. Ind. Appl. 39(6), 1596–1601 (2003)
3. Sano, K., Takasaki, M.: A surgeless solid-state DC circuit breaker for voltage source converter based HVDC systems. IEEE Trans. Ind. Appl. 50(4), 2690–2699 (2014)
4. Zhang, W., et al.: Multi-terminal HVDC grids with inertia mimicry capability. IET Renewable Power Gener. 10(6), 752–760 (2016)
5. Rouzbehi, K., et al.: Unified reference controller for flexible primary control and inertia sharing in multi-terminal voltage source converter-HVDC grids. IET Gener. Transm. Distrib. 11(3), 750–758 (2017)
6. Sammuel, A., et al.: Feasibility of a DC network for commercial facilities. IEEE Trans. Ind. Appl. 39(5), 1499–1507 (2003)
7. Agustoni, A., et al.: LV DC distribution network with distributed energy resources: Analysis of possible structures, CIRED 2005 – 18th International Conference and Exhibition on Electricity Distribution, Turin, Italy, 6–9 June 2005, pp. 1–5. https://doi.org/10.1049/cp:20051229
8. Weiss, R., et al.: Energy efficient low-voltage DC-grids for commercial buildings, 2015 IEEE First International Conference on DC Microgrids (ICDCM), Atlanta, GA, 7-10 June 2015, pp. 154-158. https://doi.org/10.1109/ICDCM.2015.7152030
9. Rodríguez Díaz, E., et al.: Voltage-level selection of future two-level Vdc distribution grids: a compromise between grid compatibility, safety, and efficiency. IEEE Electrif. Mag. 4(2), 20–28 (2016)
10. Tan, L., et al.: Effective voltage balance control for three-level bidirectional dc–dc converter based electric vehicle fast charger, 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA), Auckland, 15–17 June 2015, pp. 357–362. https://doi.org/10.1109/ICIEA.2015.7334139
11. Jiang, C., et al.: Droop control of current-source converters in bipolar-type DC microgrid, 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Brisbane, QLD, 15–18 Nov. 2015, pp. 1–5. https://doi.org/10.1109/APPEEC.2015.7380946
12. Tofoli, E.L., et al.: Survey on non-isolated high-voltage step-up dc–dc topologies based on the boost converter. IET Power Electron. 8(10), 2044–2057 (2015)
13. Deng, F., Chen, Z.: Control of improved full-bridge three-level DC/DC converter for wind turbines in a DC grid. IEEE Trans. Power Electron. 28(1), 314–324 (2013)
14. Grbovic, P., et al.: A bidirectional three-level DC-DC converter for the ultracapacitor applications. IEEE Trans. Ind. Electron. 57(10), 3415–3430 (2010)
15. Chagas, N.B., Marchesan, T.B.: Analytical calculation of static capacitance for high-frequency inductors and transformers. IEEE Trans. Power Electron. 34(2), 1672–1682 (2018)
16. Tseng, K.-C., et al.: Novel isolated bidirectional interleaved converter for renewable energy applications. IEEE Trans. Ind. Electron. 66(12), 9278–9287 (2019)
17. Lumbrares, S., Ramos, A.: Optimal design of the electrical layout of an offshore wind farm applying decomposition strategies. IEEE Trans. Power Electron. 28(2), 1434–1441 (2013)
18. Zhao, B., et al.: Overview of dual-active-bridge isolated bidirectional dc–dc converter for high-frequency-link power conversion system. IEEE Trans. Power Electron. 29(8), 4091–4106 (2014)
19. Chaoran, Z., et al.: Current Status and Development of Fault Current Limiting Technology for DC Transmission Network. 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Xi’an, 3–6 July 2019, pp. 306–310. https://doi.org/10.1109/PEDG.2019.8807665
20. Costa, L.F., et al.: Optimum design of a multiple-active-bridge DC-DC converter for smart transformer. IEEE Trans. Power Electron. 33(12), 10112–10121 (2018)
21. Du, S., et al.: A novel medium-voltage modular multilevel dc–dc converter. IEEE Trans. Ind. Electron. 63(12), 7979–7949 (2016)
22. Gowaid, A., et al.: Modular multilevel structure of a high power dual active bridge DC transformer with stepped two-level output, 16th European Conference on Power Electronics and Applications, Lappeenranta, Finland, 26–28 Aug. 2014, pp. 1–10. 10.1109/EPE.2014.6911044
23. Guo, Z., Sun, K.: Three-level bidirectional DC-DC converter with an auxiliary inductor in adaptive working mode for full-operation zero-voltage switching. IEEE Trans. Power Electron. 33(10), 8537–8552 (2018)
24. Wang, C., et al.: A 1-kW CLTCL resonant DC-DC converter with restricted switching loss and broadened voltage range. IEEE Trans. Power Electron. 33(5), 4190–4203 (2018)
25. Zhao, B., et al.: Comparative analysis of multilevel-high-frequency-link and multilevel-DC-link DC-DC transformers based on MMC and dual-active bridge for MVDC application. IEEE Trans. Power Electron. 33(3), 2035–2049 (2018)
26. Chengyong, Z., et al.: Overview on typical schemes for active control of fault current in flexible DC grid. Autom. Electr. Power Syst. 44(5), 3–13 (2020). https://doi.org/10.7500/AEPS20190626003
27. Xin, H., et al.: Modular DC power flow controller with current limiting function and its control. Autom. Electr. Power Syst. 44(5), 38–46 (2020). https://doi.org/10.7500/AEPS20190730005
28. Yalou, L., et al.: Unified terminal and highly efficient electromagnetic transient model of hybrid modular multilevel converter with various sub-modules. Autom. Electr. Power Syst. 44(5), 138–145 (2020). https://doi.org/10.7500/AEPS20190715001
29. Bin, L., et al.: Design of DC power supply for self-adaptive current-limiting solid-state circuit breaker. Autom. Electr. Power Syst. 44(5), 30–37 (2020). https://doi.org/10.7500/AEPS20190418012
30. Xu, G., et al.: Hybrid-bridge-based DAB converter with voltage match control for wide voltage conversion gain application. IEEE Trans. Power Electron. 33(2), 1378–1388 (2018)
31. Pahelevani, M., et al.: Digital current sensorless control of current-driven full-bridge DC/DC converters. IEEE Trans. Power Electron. 33(2), 1797–1815 (2018)
32. Buticchi, G., et al.: Lifetime-based power routing of a quadruple active bridge DC/DC converter. IEEE Trans. Power Electron. 32(11), 8892–8903 (2017)
33. Zhan, C.S., et al.: A current-sharing method for interleaved high-frequency LLC converter with partial energy processing. IEEE Trans. Ind. Electron. 67(2), 1498–1507 (2020)
34. Pipelzadeh, Y., et al.: System stability improvement through optimal control allocation in voltage source converter based high-voltage direct current links. IET Gener. Transm. Distribs. 6(9), 811–821 (2012)
35. Salas Bayo, A., et al.: Analysis and control interactions in multi-infeed VSC-HVDC connections. IET Gener. Transm. Distribs. 10(6), 1336–1344 (2016)
36. Zhuo, C., et al.: Research on Current Limiting Method Used for Short Circuit Fault Current of Resonant DC Transformer Based on Inverted Displacement Phase Control, in IEEE Access, vol. 8, pp. 143412–143422, 2020. https://doi.org/10.1109/ACCESS.2020.3014235
37. Zhang, C., et al.: Properties and physical interpretation of the dynamic interactions between voltage source converters and grid: electrical oscillation and its stability control. IET Power Electron. 10(8), 894–902 (2017)
38. Jiaxin, Y., et al.: Optimal design of parameters for high voltage DC fault current limiter with permanent-magnet-biased saturation. Autom. Electr. Power Syst. 44(13), 135–142 (2020). https://doi.org/10.7500/AEPS20190920011

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