

Active Converter Injection-based Protection for a Photovoltaic DC Distribution System

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Abstract—Due to the complex structure of flexible DC distribution systems with distributed photovoltaic power, single-ended measurement based protection cannot work well. The DC line-to-line faults are also difficult to locate due to a short time span with fault characteristics that is affected by various converter structures and control algorithms. To resolve these issues, a new fault detection and location method based on active converter injection is presented. The proposed method modifies the converter to become a frequency-controllable injection source by actively utilizing the coordinated control between local protection and the converters, which can build a clear protection boundary. Moreover, this method can locate the faulted area accurately by selecting the appropriate injected harmonic frequency, which is affected by the outlet capacitance of the DC/DC converter and the cable-distributed capacitance. Compared with current DC protection techniques, this method does not require additional injection equipment and high data sampling frequency. Hardware tests and simulation results are carried out, illustrating that the proposed mechanism is effective to achieve both control and protection through the controllability of power electronics.

Index Terms—Flexible DC distribution system, Distributed photovoltaic, Frequency characteristics, Harmonic impedance, Active protection.

I. INTRODUCTION

Multi-terminal and distributed DC power systems have been studied and developed extensively. They display numerous advantages over existing AC networks, including higher energy efficiency, improved reliability and power quality [1-3]. Moreover, DC distribution systems have the potential to support future smart grids by facilitating a high penetration of distributed renewable energy powers and DC loads [4-7]. However, protection for multi-terminal DC distribution systems is inhibited by lack of accurate fault detection, location and fast isolation of faulted areas, along with no distinct standards and guidelines.

A flexible DC distribution system contains both voltage-source converters (VSCs) and DC/DC converters. The structures of different converters have individual requirements

for system protection performance. Without an additional fault current limiter or DC circuit breaker, converters such as two-level VSC, modular multilevel converter (MMC), and direct-current transformer (DCT), are vulnerable to DC faults [8]. Hence a clamp double sub-module modular multilevel converter (CDSM-MMC) topology and dual-active bridge unit transformer (DAB) with a strong ability to block fault current have been utilized together in many recent projects [9][10]. In this case, the major challenge for protection is that when a DC line-to-line (pole-to-pole) fault occurs, the large fault current makes converters blocked within 1-2 ms, and the system cannot provide effective fault information for protection.

The developed DC system protection algorithms can be classified as passive method and active method. According to whether communication channels and remote end information are required, passive methods can further be divided into single-end protection (non-unit protection) and double-ended protection (unit protection). For the former, the faulty line can be identified with only local measurements. Current derivative (di/dt & $d2i/dt^2$), under-voltage and voltage derivative based non-unit protections [11][12] have been successfully applied to detect fast-changing DC fault currents with satisfactory results. However, these methods fail to provide a clearly protected boundary, which will affect relay operation selectivity. The voltage changing rate on the limiting reactor is utilized as the protection criteria in [13], to achieve the selectivity requirement. However, reactors located at the DC side may affect the dynamic performance of VSC-DC distribution. In summary, without a clear boundary, it is difficult for single-end measurement based protection to identify all faults on the protected line within 1-2 ms.

To achieve clear protection zones, many double-ended protection algorithms are proposed. Among them, differential protection [14][15] is straightforward, but the transient current of line-distributed capacitance can affect the reliability of it. A low-pass filter can remove the transient current of the line-distributed capacitor, but will affect the protection speed. Alternative research in [16] proposes pilot protection based on the transient voltage of DC-limiting reactors, while in [17], an event-based protection scheme identifies faults in the current-changing rate with the help of communication. Both types of protection demonstrate satisfactory performance, but they can only be utilized in a system with limiting reactors.

In addition, most active methods are proposed in the low voltage and medium voltage DC grid. The active methods [18-21] install additional devices and acquire the specific signal injection for fault detection and location. Their main drawback is extra equipment that might be not allowed by

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utilities for reliability reasons. Moreover, when the structures of branches are complex in the DC distribution networks, the locating results are prone to getting the false fault points. Therefore, developing a new protection principle with good selectivity and reliability is essential.

Based on these issues, this paper proposes a novel fault detection and location method based active protection for flexible DC distribution systems with multi-terminal photovoltaic (PV). The main contributions of this paper are:

- 1) The proposed method utilizes the coordinated control between local protection and the converters in the system, thereby the converter can be turned into an injection source with known characteristic signal for protection.
- 2) Most existing DC protections focus on distinguishing the faulted line section, but it still takes a lot of time to identify the exact fault point to remove the fault. The proposed protection method can locate the fault point by calculating the harmonic impedance of these characteristic signals. As a result, it can isolate the fault line, and at the same time, the DC fault can be removed. That greatly shortens the system recovery time.
- 3) The performance of the proposed protection is compared with existing methods to show that the proposed technique offers better performance and does not require additional injection equipment or modification of the system configuration.

II. ANALYSIS OF THE CONVERTER FAULT PROCESS

A multi-terminal DC distribution system based practical project [22] is selected as the research object (Fig. 1). The six PV power plants are boosted to ± 10 kV through the DAB on-site, and then are connected with each other via DC cables to form a ring system. Among them, DAB is composed of H bridges on both sides, and a high-frequency transformer. The voltage level on each side of the DAB can be controlled by adjusting the pulse width of the H bridges, and the high-frequency transformer acts as an electrical isolation component.

The ring system is then connected with the AC system through CDSM-MMC to achieve bidirectional power flow of the AC and DC system. The AC/DC converter adopts constant DC voltage control on the DC side and the working mode for the DABs in normal operation is equivalent to a current source. The system also contains two energy storage devices to balance the PV power output. At the same time, to ensure that the converter equipment is not damaged during the interruption of the fault current by the DC breaker, a current limiting reactor is configured at the outlet of each PV port.

Control and protection of the multi-terminal DC distribution system is realized through the communication of the converters. The unit layer controls (controls of DC/DC converters) have the ability to switch the modulation frequency of the local converter. Coordination and cooperation between multiple converters can be achieved through communication network (Generic Object Oriented Substation Event, GOOSE technology) to realize the information transfer between the

local protection and the converters. Hence, the local converter can be turned into an injection source with a characteristic frequency signal by changing the modulation frequency of the local converter after the fault.

Generally, DC-side neutral points are connected to earth through high impedance in practical engineering [23]. For the line-to-ground fault, the fault line is clamped to zero potential, and due to the support of the converter sub-module capacitor, the non-faulty pole voltage rises to twice the pre-fault voltage, but the voltage between the poles remains unchanged [24]. Hence, DC line-to-ground faults do not cause over-current damage and DC voltage unbalance protection is configured for line-to-ground fault. Thus, this paper mainly focuses on DC line-to-line faults.

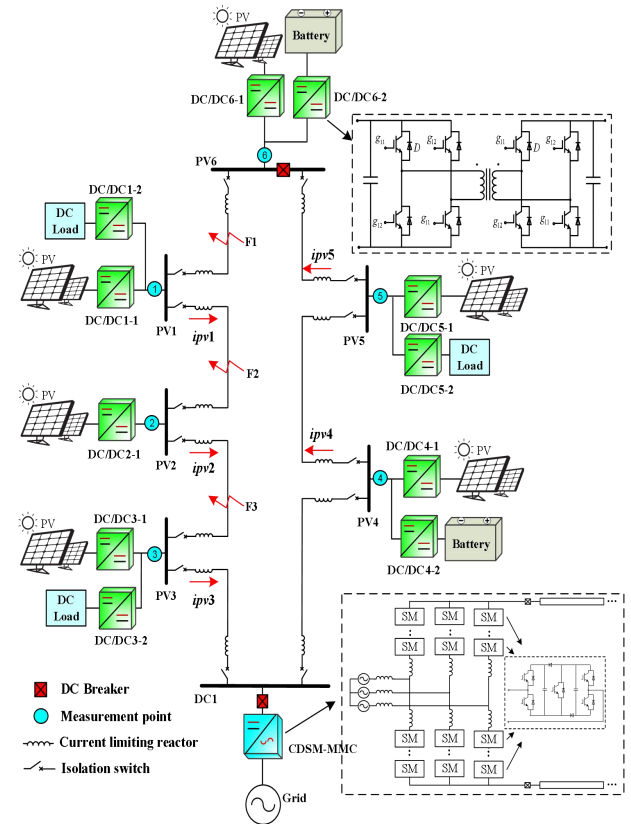


Fig. 1. Structure of multi-terminal flexible DC distribution system.

A. Fault Characteristics of CDSM-MMC

During a DC line-to-line fault, the fault transient of a CDSM-MMC can be divided into two stages according to the fault progression time, namely the DC fault “detection stage” and the DC fault “isolation stage”, as shown in Fig. 2.

Stage 1: During the “detection stage”, the equivalent circuit is a second-order function for solid faults as shown in Fig. 2(a). The circuit natural response provides an oscillation under the condition of $R < 2\sqrt{L/C}$, where L represents the equivalent value of bridge arm reactor inductance, C is the equivalent capacitance of the converter, and R denotes the series resistance in the capacitor and contact resistance in the discharge circuit. When the initial condition of the equivalent sub-module capacitor voltage is U_{dc} and the load current is I_0 , the natural response can be presented as:

$$\begin{cases} i_{dc}(t) = (U_{dc}/\omega L)e^{-\delta t} \sin(\omega t) - (I_0\omega_0/\omega)e^{-\delta t} \sin(\omega t - \beta) \\ u_C(t) = (U_{dc}\omega_0/\omega)e^{-\delta t} \sin(\omega t + \beta) - (I_0/C\omega)e^{-\delta t} \sin(\omega t) \\ \beta = \arctan(\omega/\delta) \end{cases} \quad (1)$$

where $i_{dc}(t)$ is the instantaneous current of positive pole line, $u_C(t)$ is the voltage of the capacitor, and their positive direction is defined from converter to fault point as shown in Fig. 2(a). The δ represents attenuation factor ($\delta = R/2L$), ω is the oscillation angular frequency ($\omega = \sqrt{1/LC - (R/2L)^2}$), and ω_0 represents the inherent angular frequency ($\omega_0 = \sqrt{\delta^2 - \omega^2}$). The converter self-protection operates at twice the rated current in approximately 1 ms, blocking the gate signal immediately, at which point the “detection stage” is finished and the next stage begins.

Stage 2: During the “isolation stage”, the series/parallel capacitance voltage provides the fault circuit with directional potential after converter blocking. The fault current of the bridge arm has two paths in different directions, as shown in Fig. 2(b). Fault path 1 consists of the Phase A upper bridge arm and Phase B upper bridge arm, while fault path 2 is formed by Phase A upper arm and Phase C lower bridge arm. Therefore, the fault currents decrease to zero during fault isolation stage as all currents are forced inflow to the capacitor of the sub-module. At the same time, the capacitor voltage increases.

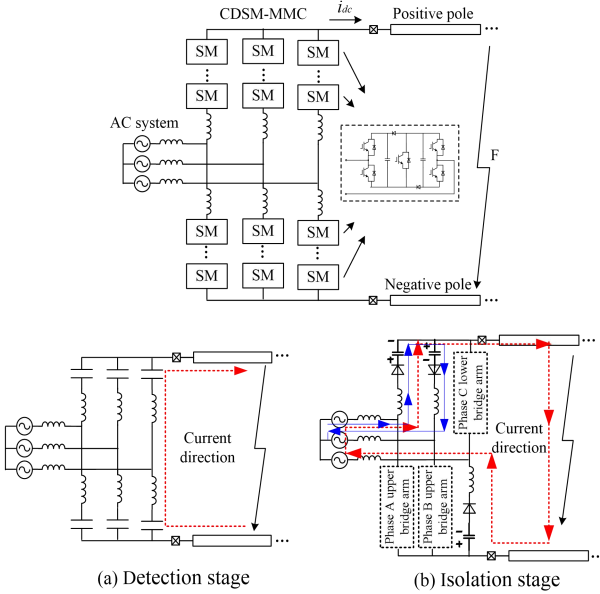


Fig. 2. Equivalent circuits of CDSM-MMC during different fault stages.

B. Fault Characteristics of DAB

Regardless of the working mode of the DAB converter, the fault transients can also be divided into two stages according to the fault progression time during a pole-to-pole fault. That is the DC fault “detection stage” and the DC fault “isolation stage”. It is assumed that the DC/DC module of the PV voltage rising transformer on the site is only composed of a single DAB sub-module. The equivalent circuit is shown in Fig. 3, in which the DC cable pole-to-pole fault occurs.

Stage 1: Due to the large voltage difference between the fault point and the outlet capacitor, the energy stored in the outlet

capacitor is rapidly discharged to the fault point when a DC pole-to-pole fault occurs, and the fault current rises suddenly to peak value. Hence, this operation can also be called the capacitor discharge process. The path is shown in line 1 of Fig. 3, and the circuit can be taken as equivalent to the RLC oscillating circuit [25]. In other words, the circuit is under the condition of an under-damped response.

Stage 2: The current rises rapidly to reach the self-protection value of insulated-gate bipolar transistor (IGBT) in DAB, then the DC/DC transformer is blocked. After blocking, the fault current forms a continuous flow path through the reactor and the reverse parallel diode in the H bridge. The path is shown in line 2 of Fig. 3. Due to the electrical isolation of the high frequency transformer in the DAB module, the DC fault current gradually attenuates to zero after DAB is blocked.

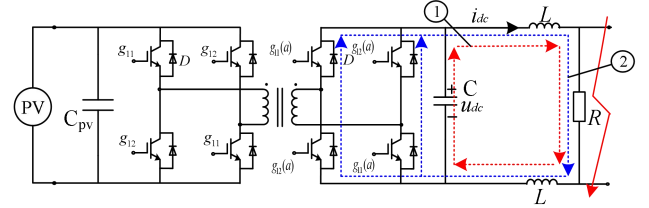


Fig. 3. Equivalent circuits of DAB under pole-to-pole fault.

In summary, according to the analysis of the fault process, the isolation stage cannot provide effective fault transient information for protection because the DC cable fault current is zero (Both CDSM-MMC and DAB have isolation stages). To solve it, the converter control is then modified to inject characteristic signal by changing the modulation frequency of the converter after the fault. The fault detection and location are achieved by the calculation and detection of these characteristic signals.

III. PROTECTION METHOD BASED ON ACTIVE CONVERTER INJECTION

A. Location of the Single-end Fault Distance

The working principle of DAB is to use a pulse width modulation (PWM) signal (square wave) with a constant frequency to control IGBT on and off in the H bridge. In the traditional PWM control mode, the frequency of the PWM signal determines the switching frequency in the DAB, and a change in the switching frequency will cause a change in the output frequency. Thus, this paper alters the switching frequency of DAB by changing the frequency of PWM trigger pulse, so it can output a fixed unique harmonic component. The output frequency of DAB can be regarded as self-defined harmonic source. In this way, by measuring the faulted harmonic line impedance between the DAB and the fault point, the fault distance can be estimated.

Because the DAB is used as a source of harmonic, it must be unblocked after the fault occurrence. In this case, the capacitor discharge process of DAB will re-start and will gradually enter a new steady state. Its equivalent circuit is illustrated in Fig. 4. where, C_{PV} represents the equivalent capacitance at the low voltage side of DAB, C_o is the outlet equivalent capacitance,

and u_{dc} is the outlet capacitor voltage. The L_l and R_l represent the DC line equivalent inductance and resistance respectively, and R_f denotes the fault resistance. As shown in Fig. 4, process of energy flow is that the PV source (constant current source) will charge the capacitor C_{PV} (Path ①), then the capacitor C_{PV} will not only charge the outlet capacitor C_o , but also provide current to the fault point through the DAB. In Fig. 4, blue arrows represent one current path including connectivity of C_{PV} , g_{11} , g_{11}' and C_o . The other path is shown as red arrows, which includes connectivity of C_{PV} , g_{12} , g_{12}' and C_o . The outlet capacitor of DAB forms a fault loop circuit (Path ②) with the DC fault line and the fault resistance.

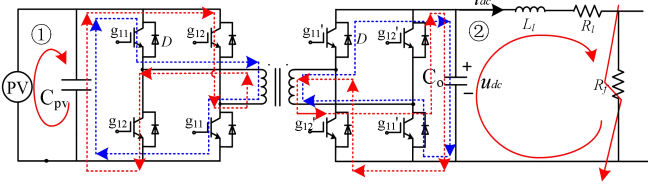


Fig. 4. Equivalent circuits of steady state after fault.

Considering that the energy stored in the outlet capacitor is very low at this time, and the voltage difference between the capacitor and the fault point is very small. Moreover, it is assumed that during the harmonic current injection of DAB, the external environment is stable and the PV output characteristics remain unchanged. Since the PV side adopts MPPT control strategy, the output current of the PV is fixed. Therefore, during the DAB unlocked, the fault current is not very high and the fault circuit will enter a new steady state shortly.

Then the PV source and DAB can be regarded as a harmonic injection source. Taking the F2 fault (in Fig. 1) as an example to analyze the fault circuit impedance, the injected harmonic current loop is illustrated in Fig. 5. The $upv6$ and $ipv6$ are the line voltage and current measured at the measurement point 6 (in Fig. 1), L_0 is the current limiting reactor inductance, R_1 and L_1 represent the resistance and inductance of DC cable per kilometer, respectively. The x indicates the DC cable length between PV1 and PV6 (in Fig. 1), and y_1 indicates the distance between fault location F2 and measurement point 1. The C_{1-1} and C_{1-2} denote the the outlet capacitor of DC/DC 1-1 and DC/DC 1-2, respectively.

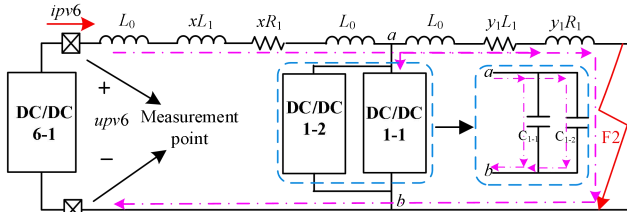


Fig. 5. Injected harmonic current loop with a DC fault.

In Fig. 5, when the DC/DC 6-1 injects the switching harmonic current, the current flows through the DC cable between measurement points and fault location F2, DC/DC 1-1 and DC/DC 1-2. Because DC/DC 1-1 and DC/DC 1-2 are

locked, the harmonic current only flows through the outlet capacitor.

According to Fig. 5, the measured DC-side voltage $upv6$ can be represented in frequency domain as:

$$U_{pv6}^f = xR_1 I_{pv6}^f + j2\pi f(xL_1 + 2L_0)I_{pv6}^f + \{[1 / (j2\pi fC_{1-1})] / [1 / (j2\pi fC_{1-2})] / [y_1 R_1 + j2\pi f(y_1 L_1 + L_0)]\} I_{pv6}^f \quad (2)$$

where f is the frequency (DAB switch frequency), and U_{pv6}^f and I_{pv6}^f are the harmonic phasors of the measured voltage and current, respectively.

Considering that DAB adopts a parallel input and output series (IPOS) structure to increase the capacity and voltage level of PV power plants, as shown in Fig. A1 of appendix, which causes the equivalent capacitance to become smaller at the output of DAB. Thus, the DC/DC converter outlet harmonic impedance is much larger than the DC line impedance. Therefore, the harmonic current can hardly pass through DC/DC 1-1 and DC/DC 1-2, and the impedance of DABs can be ignored. Then, (2) can be simplified as:

$$U_{pv6}^f = xR_1 I_{pv6}^f + j2\pi f(xL_1 + 2L_0)I_{pv6}^f + [y_1 R_1 + j2\pi f(y_1 L_1 + L_0)]I_{pv6}^f \quad (3)$$

According to (3), the measured impedance Z_{pv6}^f and fault distance can be obtained by:

$$Z_{pv6}^f = U_{pv6}^f / I_{pv6}^f = j2\pi f3L_0 + (R_1 + j2\pi fL_1)(x + y_1) \quad (4)$$

$$x + y_1 = (Z_{pv6}^f - j2\pi f3L_0) / (R_1 + j2\pi fL_1) \quad (5)$$

It should be noted that if the switching harmonic frequency is too high or the system parameters are different from this paper, the impedance of DABs may not be ignored, but the fault distance can still be calculated by (2).

Accurately extracting the harmonic component from measurements is a vital component of the proposed fault location method. Therefore, in order to rapidly locate faults, the windowed Fourier algorithm is used (about one cycle of custom frequency).

B. Protection Scheme of Flexible DC Distribution System with Multi-terminal Distributed PV Power

The fault area can be roughly determined by calculating the harmonic impedance, but it will be influenced by measurement errors and cannot precisely cover the whole line without using coordination. Therefore, in order to solve the selectivity problem of single-end protection, this paper utilizes the inter-station communication of the converters to unlock different DABs with alternate injection frequencies. By this way, there are two injection sources with different frequencies in the system, achieving the selectivity of the protection. The detailed flow is as follows.

1) The di/dt and du/dt are used as the starting criteria of the proposed method to detect if there is unusual system operation and start the protection.

2) After the protection is started, the current of each measuring point (including the measuring point in the DC circuit breaker) is used to estimate whether it is over-current. If the line current is greater than the setting value, the blocking

signal is sent to the local converter (DC/DC, DC/AC). Meanwhile, the DC breaker starts to operate.

3)The ring system is loop-opening after 7 ms as the operation time of the DC breaker is about 5 ms. Then, the DC/DC (6-1) is unlocked by using the station level control, and the switching frequency is changed to output the characteristic harmonic component.

4)The harmonic current and voltage components at the measurement point 6 are extracted by a windowed Fast Fourier transform (FFT). The harmonic impedance value is then calculated, and the fault distance ($x+y_1$) is roughly determined.

5)Taking the F2 fault in Fig. 1 as an example. The calculation of harmonic impedance cannot distinguish the fault at the end of the cable from the fault at the start of the next cable section, such as the fault point F2 and F3, when their electrical distance is very short. Therefore, inter-station communication is used to let DC/DC (6-1) send the unlocked signal to DC/DC (3-1) and change its switching frequency to output the harmonic component different from DC/DC (6-1).

6)The maximum frequency component is acquired from the spectrum, which is extracted from the current data of the measuring point 2 by FFT, to determine whether it is provided by the DC/DC (6-1). If true, the fault point is at the start of the next cable. If not, the fault point is considered to be at the end of the upper cable.

7)The fault location is finally determined and all the converters in the system will be blocked again. The isolation switches on both sides of the corresponding fault cable will be opened and the system commences restoration.

In summary, the fault area is roughly determined by step 3 and step 4, the protection selectivity and the accurate fault location are achieved through step 5 and step 6. Moreover, the maximum time from the protection starting to protection reset is 23 ms. This includes 3 ms time of the over-current detection and relay protection signal communication, 5 ms operation time of the DC circuit breaker, 5 ms initial locating time of the fault area (the window time for calculating the impedance for the first time), 5 ms second locating time of the fault area (the window time for calculating the maximum frequency component), 1 ms total time of converter-to-converter communication and converter control switching, and 3 ms isolation switch operation time. Meanwhile, there may be more delay time about 1 ms in the real hardware system, such as some stray time of data packing and logic signal communication.

C. Influence of the Cable-distributed Capacitance

Cable distributed capacitance and cable distributed inductance are the basis of the traveling wave. Therefore, the frequency of the distributive current of capacitance and inductance is consistent with the natural frequency of the traveling wave. The natural frequencies of traveling waves are related to fault distance and boundary conditions. The mathematical relationship is:

$$f_s = \frac{(\theta_S + \theta_F + 2k\pi)v}{4\pi d}, k = 0, \pm 1, \pm 2 \quad (6)$$

where v is traveling wave velocity, d is the fault distance, θ_S is the reflection coefficient angle at the beginning of the line, and θ_F is the reflection coefficient angle at the fault point. The numeric area of θ_S (the reflection coefficient angle at the beginning of the line) is 0 to π . For both a metal fault or transitional resistance fault reflection, the coefficient angle θ_F at the fault point is 0. Therefore, the theoretical minimum value of the natural frequency of the traveling wave is:

$$f_{s\min} = \frac{v}{4d} \quad (7)$$

For the high frequency component of the traveling wave, the wave velocity v is about 97%~99% of the optical speed. Considering that the transmission distance of the ± 10 kV DC distribution system is generally within 40 km (d will not exceed 40 km), $f_{s\min}$ can calculate that the main frequency of the natural frequency will be no less than 1800 Hz.

In summary, the frequency of the injection source is 200 Hz or 300 Hz for the method proposed in this paper. Compared to distributive capacitance current frequency and distributive inductance current frequency, this number is within the low frequency range. Therefore, in theory, cable distributed capacitance and cable distributed inductance will not affect the performance of the proposed method.

IV. HARDWARE TESTING AND SIMULATION

The foundation of the proposed protection which involves altering the DAB output frequency is verified by a scaled-down hardware testing system. This test mainly focuses on whether DAB can change the switching frequency during steady state, and the switching harmonics still exist during the fault transient. That can be used to calculate the harmonic impedance to determine the fault distance roughly. The full performance of the proposed method is further tested in a complicated simulation system.

A. Experiment Verification

To evaluate the performance of the proposed method, a simple 750 V DC experimental platform with DAB is built as depicted in Fig. 6. The hardware testing system contains VSC, DAB, and DC source. The DC source is a DC power source and load unified intelligent simulator and can simulate PV output characteristics. The VSC adopts constant DC voltage control. The rated capacity of the VSC is 10 kW, the phase-to-phase capacitance is 1260 μ F, and the AC-side reactor is 12.5 mH. Additionally, the rated capacity of the DAB is 10 kW and the ratio of transformation is 760:100. The high voltage side capacitance is 1.64 mF and low voltage side capacitance is 3.28 mF. The R_l and L_l is used to represent cable resistance and inductance, R_l is 0.06 Ω , L_l is 0.1mH. The R_f is fault resistance that is set to 5 Ω . The DAB utilizes phase-shifting modulation with square wave. The whole test bed is placed in four cabinets, as in Fig. 7.

The current waveform is measured at the measurement point M in Fig. 6. Changing process of the DAB switching frequency is shown in Fig. 8. To verify the correlation between the output current frequency and the switching frequency, the current

waveform is extracted and analyzed by the FFT, and the results are provided in Fig. 9.

As in Fig.10, when a DC pole-to-pole fault occurs at 0.25 s, the fault current rises sharply and the DAB is locked rapidly for over-current, which meets the starting criteria of the proposed protection scheme. Thus, the proposed protection can operate reliably. Then the DAB is unlocked and injects switching harmonic by manual operation. Due to the lack of internal communication network in the experimental platform, it takes longer than the practical project. In order to present a coherent control process, this period of operation time is not shown in Fig. 10. During the injection of DAB, the fault current fluctuates with the switching frequency and does not have rush feature. In fact, from the occurrence of a DC short-circuit fault to the unlocking of the DAB, the fault circuit is not changed for the outlet capacitor and will enter a new steady state shortly.

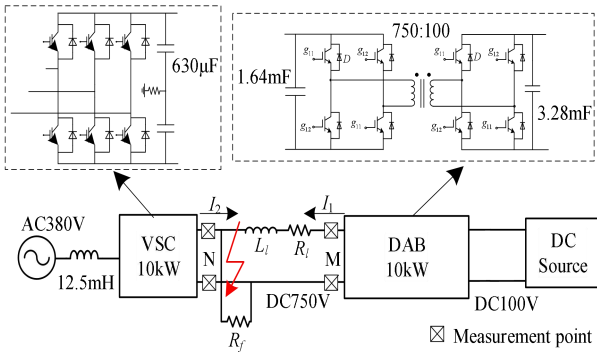


Fig. 6. Topology of VSC-DC system with DAB.

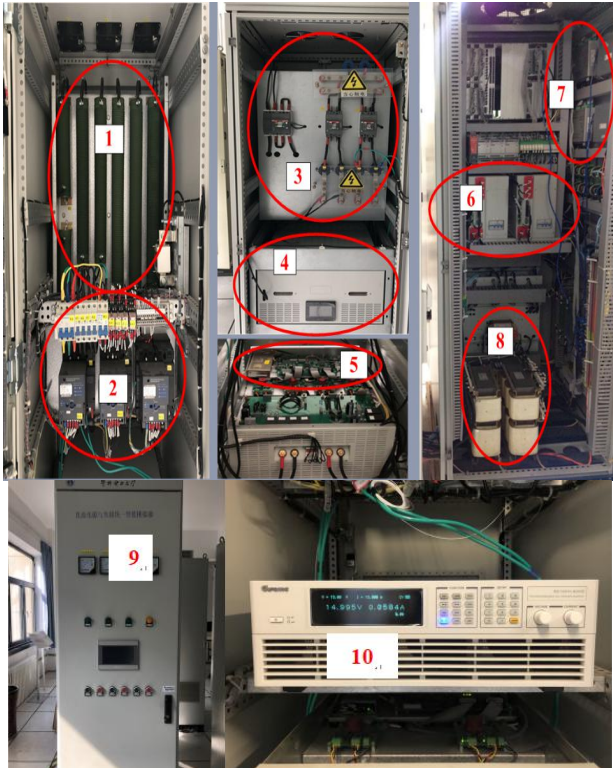


Fig. 7. Scaled-down hardware test bed of VSC-DC system with DAB load resistance; 2. load switches; 3. 750V switches; 4. DAB; 5. control units of DAB; 6. VSCs; 7. control units of VSCs; 8. reactors; 9. DC power source and load unified intelligent simulator; 10. controller of the simulator.

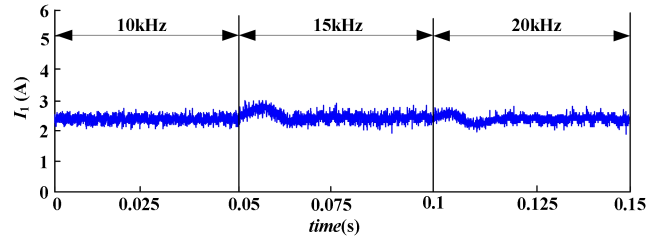


Fig. 8. DC current waveform during steady state with different switching frequency of DAB.

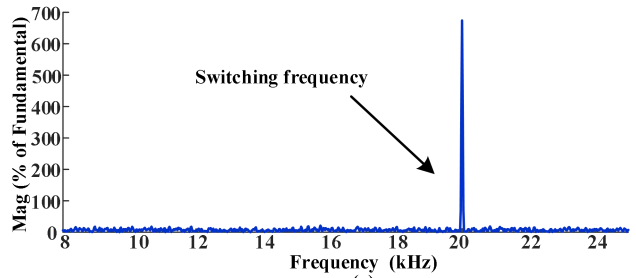
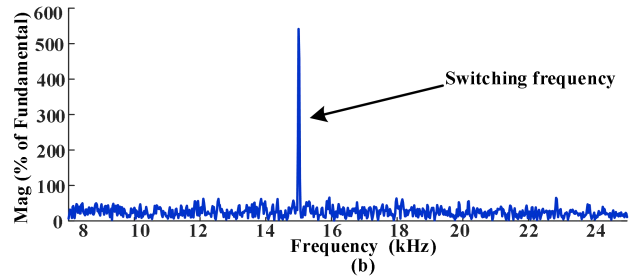
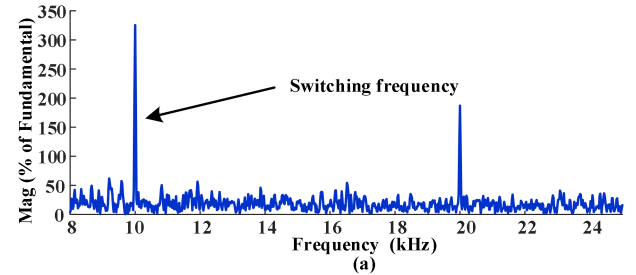


Fig. 9. Analysis results of current waveform using FFT.

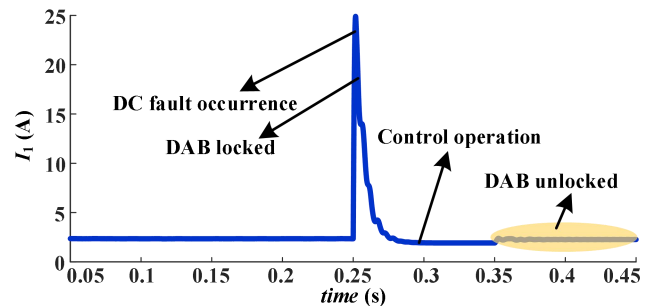


Fig. 10. DC current waveform during a DC fault with switching frequency of 20kHz.

To verify the existence of switching harmonics during fault transient, the spectrum of fault transient current (orange shade) is provided in Fig. 11. It can be seen that the switching frequency harmonic is still the largest. Then according to (4), the harmonic impedance calculation result is 11.76Ω , and the actual value is 11.35Ω , the error is acceptable.

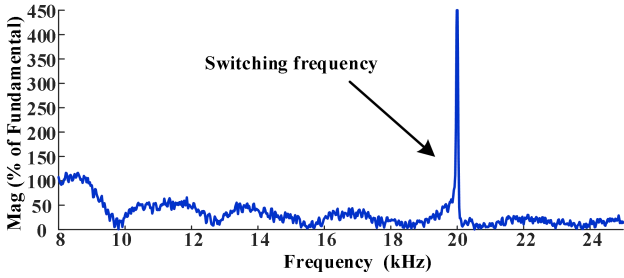


Fig. 11. Analysis results of fault transient current waveform using FFT.

B. Simulation Verification and Analysis

To comprehensively verify the feasibility of the proposed method, a ± 10 kV flexible DC distribution system with multi-terminal distributed PV shown in Fig. 1 is built in PSCAD/ EMTDC. The number of DAB adopting IPOS structure is 10 at each PV station, the outlet capacitance of a DAB is 50 μ F, and the current-limiting reactor reactance is 0.1mH. Detailed parameters of the system are provided in Appendix A. Moreover, the insulation level of PV array in the simulation is assumed normal and compliant with IEC 61215 standards, therefore the PV array can output normally during conducting fault location.

Based on this topology and the fault point of F2, the theoretical value Z of the equivalent impedance is calculated at the measuring point of the PV6 converter output. The data sampling frequency is 10 kHz, and the protection operation is carried out as described in Section III. B.

The fault currents measured near the six different DC/DC converter output during the F2 fault are provided in Fig. 12. It can be observed that the fault occurs at 0.35 s. After the fault, the currents rise rapidly and meet both operation thresholds of converter self-protection and the DC circuit breaker. Thus, the proposed protection can operate reliably. The ring system is loop-opening by the DC circuit breaker after approximately 7 ms. In this case, the system diagram of Fig. 1 is equivalent to Fig. 13. Meanwhile, the station level controls unlock the DC/DC converter (6-1) and change the switching frequency (to 200 Hz). It can be seen that the system enters a steady state after the fault, as shown in Fig. 12. While current i_{pv6} fluctuates with the frequency of 200 Hz. Hence, the DC/DC (6-1) can be regarded as a harmonic injection source and the circuit diagram can be simplified as Fig. 5. Then by calculating the harmonic impedance, the fault area is determined to be about 3 km from the measurement point (Reference formula (2)-(5) in Section III).

In order to distinguish between the fault at the end of the cable (F2 in Fig. 13) and the fault at the start of the next cable (F3 in Fig. 13), after the fault area is roughly determined, the DC/DC (6-1) control system transmits the unlocking signal to DC/DC (3-1) and changes its switching frequency to 300 Hz. This explains the fluctuation of 300 Hz existing in i_{pv3} , shown in Fig. 12. The current data derived from measurement point 2 is used to calculate maximum frequency component by FFT with 200Hz fundamental frequency. The largest content is 300 Hz (the characteristic frequency of DC/DC (3-1)), which is shown in Fig. 14. This proves that there is no fault between

measuring point 2 and measuring point 3, as the injected characteristic frequency signal (300 Hz) cannot bypass the fault point.

These phenomena show that the coordinated harmonic injection is achieved and provides a guarantee for the well performance of the proposed protection.

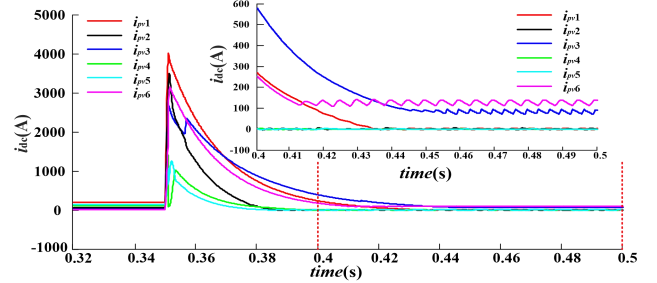


Fig. 12. Simulation of DC current waveform under F2 fault.

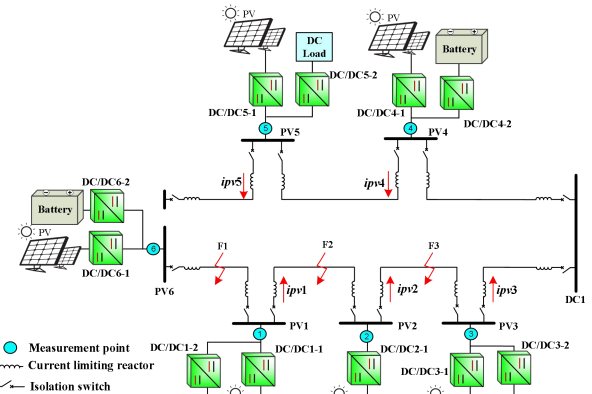


Fig. 13. Structure diagram of system.

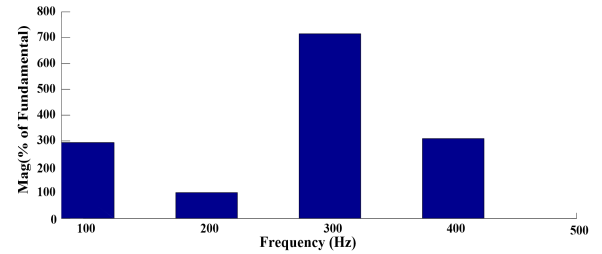


Fig. 14. FFT analysis result of measurement point 2.

The performance of the proposed method evaluated under the different factors (fault distance, noise, cable-distributed capacitance, and fault resistance) is illustrated in Table I and Table II, where E represents the error of estimated fault distance. As shown in Table I, different fault distances are simulated. The results indicate that the protection can operate correctly for all faults in the protected line, regardless of the fault distance. Additionally, to verify the proposed method with measurement noise, 40 dB Gaussian noise is superimposed on measurements of each test. By comparison, the error of estimated fault distance under 40 dB noise illustrates that the result is slightly influenced, but the fault area can be determined and the error is still less than 2% under 40 dB noise. It is known that noise may affect the current waveform, but noise seldom affects the main harmonic

components in the waveform. The main theoretical reason for this is that the random noise cannot inundate the frequency of the special signal injection source.

Considering that pole-to-pole faults in DC cables are commonly caused by external damage and most are solid faults, it is sufficient to set a $5\ \Omega$ resistor, which is equivalent to hundreds of kilometers cable. As in Table I, the fault area can be detected and the error is still less than 2%. Thus, the protection proposed can correctly identify the fault area and meet the sensitivity requirements.

To analyze the influences of distributive capacitances and distributive inductances of the DC line, twice and four times of the original value are set, respectively. As shown in Table II, the calculation results illustrate that the proposed protection method can still distinguish the correct faulted area with different distances, different line capacitances and inductances. The relative error in all cases is within 2%, and the result is stable. The main reason is that the frequency of the injection source is 200 Hz or 300 Hz for the proposed method, which is a much lower frequency than the frequency of the distributive capacitance current and distributive inductance current. Therefore, the cable distributed capacitance and inductance will not affect the performance of the proposed method. Simulation results also verify the accuracy of the theoretical analysis.

C. Comprehensive Comparison with Existing Methods

As shown in Table III, the performance of the proposed protection is compared with existing methods. In terms of speed (fault clearing time), the non-unit protections have more advantage for no communication delay. In terms of selectivity, the unit protections have a clear boundary and can trip the fault

with high resistance. The selectivity of other active protections can be greatly affected by the multiple branches of the DC distribution networks, but the proposed protection has the better selectivity due to the communication. In terms of reliability, active protection and the proposed protection are good options. The injection based method have unique fault features and are not affected by the variable fault transient components. However, since the proposed protection method requires a communication network, and when the communication network is attacked, its reliability will be greatly affected. Therefore, it just be ranked with two stars. In terms of economy, the proposed protection has more advantage. Compared with other active protections, the proposed technique does not require additional injection equipment and high data sampling frequency. In terms of fault location accuracy, active protection and the proposed protection can offer better results.

TABLE I SIMULATION RESULTS OF THE PROPOSED METHOD

Fault Point (km)	Noise				Fault resistance	
	0dB	E /%	40dB	E /%	5 Ω	E /%
1	0.986	1.40	1.011	1.10	1.011	1.10
2	2.031	1.55	1.974	1.30	1.974	1.30
3	3.047	1.56	3.052	1.73	3.047	1.56
4	4.061	1.52	4.066	1.65	4.061	1.52
5	5.075	1.50	4.911	1.78	5.075	1.50
6	6.091	1.51	6.109	1.81	6.089	1.48
7	7.115	1.64	6.893	1.52	7.115	1.64
8	7.889	1.38	8.134	1.67	7.889	1.38
9	8.872	1.42	9.153	1.70	8.872	1.42
10	9.853	1.47	9.875	1.25	9.875	1.25

TABLE II SIMULATION RESULTS OF THE PROPOSED METHOD

Fault Point (km)	Cable distributed capacitance (uF/km)						Cable distributed inductance (mH/km)					
	0.0073	E /%	0.0146	E /%	0.0292	E /%	0.3	E /%	0.6	E /%	1.2	E /%
1	0.986	1.40	0.986	1.40	0.985	1.50	0.986	1.40	1.011	1.10	0.982	1.80
2	2.031	1.55	2.029	1.45	2.028	1.40	2.031	1.55	1.974	1.30	1.974	1.30
3	3.047	1.56	3.045	1.50	3.047	1.56	3.047	1.56	3.052	1.73	2.977	1.15
4	4.061	1.52	4.063	1.57	4.063	1.57	4.061	1.52	4.066	1.65	3.951	1.22
5	5.075	1.50	5.075	1.50	5.073	1.46	5.075	1.50	4.911	1.78	5.073	1.46
6	6.091	1.51	6.089	1.48	6.092	1.53	6.091	1.51	6.109	1.81	5.905	1.58
7	7.115	1.64	7.116	1.65	7.107	1.52	7.115	1.64	6.893	1.52	7.107	1.52
8	7.889	1.38	7.874	1.57	7.886	1.42	7.889	1.38	8.134	1.67	8.155	1.93
9	8.872	1.42	8.868	1.46	8.865	1.50	8.872	1.42	9.153	1.70	9.171	1.90
10	9.853	1.47	9.856	1.44	9.847	1.53	9.853	1.47	9.875	1.25	9.840	1.63

TABLE III COMPREHENSIVE COMPARISON WITH EXISTING METHODS

Method name		Source	Speed	Selectivity	Reliability	Economy	Location	Special requirement	Comprehensive performance	
Passive protection	Non-unit Protection	Current derivative	[11]	★★★	★	★	★★★	No	high-bandwidth measurement	8★
		Voltage derivative	[12]	★★★	★	★	★★★	No	Reactor	8★
	Unit protection	Current differential	[13]	★★★	★	★	★★★	No	Reactor	8★
		Current differential	[14]	★★	★★★★	★★	★★	No	synchronized communication	9★
		Transient information of reactor	[15]	★★	★★★★	★★	★★	No	Communication and reactor	9★

Active protection	Active injection	[18]	★	★★	★★★	★	★★★	Additional equipment	10★
	Proposed protection	[19]	★	★★★	★★	★★	★★★		

“★★★” represents the best performance; “★” represents the worst performance;

V. CONCLUSIONS

An active protection scheme for flexible DC distribution systems with multi-terminal distributed PV is proposed in this paper. Hardware tests and simulation results illustrate that the method can accurately locate the faulted area when the injected harmonic frequency is selected appropriately, and is effective for achieving a combination of control and protection through the controllability of power electronics. Compared with the published DC protection method, this technique does not require additional injection equipment and high data sampling frequency. The proposed method is also unaffected by measuring noise and cable distributed capacitance. The new protection is therefore feasible for industry application in a large and complex DC network.

APPENDIX

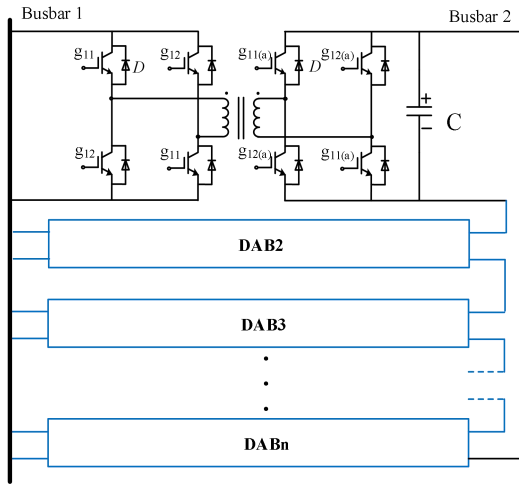


Fig. A1. IPOS structure diagram of DABs.

TABLE A.I
PARAMETERS OF CONVERTERS

Parameter name	Voltage ratio	Power capacity	Control strategy
AC/DC	AC10kV/DC10kV	10MW	Constant voltage
DC/DC1-1	DC10kV/DC750V	5MW	MPPT
DC/DC2-1	DC10kV/DC750V	2MW	MPPT
DC/DC3-1	DC10kV/DC750V	2MW	MPPT
DC/DC4-1	DC10kV/DC750V	4MW	MPPT
DC/DC5-1	DC10kV/DC750V	3MW	MPPT
DC/DC6-1	DC10kV/DC750V	0.5MW	MPPT
DC/DC1-2	DC10kV/DC750V	1.5MW	Constant power
DC/DC3-2	DC10kV/DC750V	1.5MW	Constant power
DC/DC4-2	DC10kV/DC750V	2MW	Constant power
DC/DC5-2	DC10kV/DC750V	1MW	Constant power
DC/DC6-2	DC10kV/DC750V	1MW	Constant power

TABLE A.II
PARAMETERS OF DC CABLES

Bus name	Length	resistance	inductance	capacitance
Head-End	(km)	(Ω/km)	(mH/km)	($\mu\text{F}/\text{km}$)
PV1-PV2	2	0.0293	0.3	0.0073

PV2-PV3	2	0.0293	0.3	0.0073
PV3-DC1	2	0.0293	0.3	0.0073
DC1-PV4	10	0.0293	0.3	0.0073
PV4-PV5	4	0.0293	0.3	0.0073
PV5-PV6	1	0.0293	0.3	0.0073
PV6-PV1	2	0.0293	0.3	0.0073

TABLE A.III
PARAMETERS OF PV ARRAY

Number of modules connected in series per array	50
Number of modules strings in parallel per array	50/20/20/40/30/5
Number of cells connected in series per module	9
Number of cells strings in parallel per module	7
Number of arrays connected in series per PV station	2
Number of arrays in parallel per PV station	10
Reference irradiation	1000W/m ²
Reference cell temperature	25°C

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