Islanding detection method for multi-terminal renewable power DC distribution system

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Abstract
Most of the traditional islanding detection methods are designed for renewable sources in AC systems and cannot be directly applied in multi-terminal DC renewable power distribution systems. Moreover, the attenuation effect of multi-branches makes it difficult for active methods to effectively detect complex islanding operations with multiple renewable power sources. To address the above problems, this paper proposes an active high-frequency impedance estimation based DC islanding detection method. The impedance of converters is proved to be a constant value at high-frequencies, and the high-frequency impedance of the system changes significantly after islanding. Therefore, islanding operations can be accurately detected through impedance characteristics with a negligible none detection zone. The proposed islanding detection method uses DC/DC converters to inject non-characteristic harmonics to perform high-frequency impedance calculations without additional injection equipment. The high-frequency impedance directly reflects structural changes of the DC system. In this case, this method has lower requirements on the disturbance intensity and will not be influenced by the attenuation effect. The injected harmonic voltage is used as an auxiliary criterion to detect complex DC islanding operations with multiple renewable sources. Simulation results prove that the proposed method has high detection accuracy and is not affected by transient conditions.

1 | INTRODUCTION

With the development of renewable power generation technology [1–4], the integration of renewable power sources through Modular Multilevel Converter (MMC) based flexible DC distribution system has become a research hot topic due to the advantages of less commutation links, higher energy conversion rate and better power quality [5–7]. Several demonstration projects of MMC-DC distribution system have been established in China [8–13]. In a DC distribution system with photovoltaic (PV) sources, unplanned islanding operations pose safety hazards to both personnel and equipment. Islanding detection method (IDM) in DC systems needs to be investigated.

At present, IDMs can be divided into communication-based methods and local measurement-based methods. Communication-based methods update switch state between distributed power sources to detect islanding operations [14, 15]. The communication devices and channels could potentially limit the application of this method. Local measurement-based methods can be further divided into passive methods and active methods. They have been fully developed in AC grid, but most of them cannot be directly applied in DC grid.

Passive methods rely on the changes of electrical quantities caused by power mismatch after islanding. Passive methods in AC systems mainly include over/under voltage methods, over/under frequency methods [16, 17], phase jump methods [18] and harmonic voltage methods [19]. DC grid does not transmit reactive power and cannot offer frequency and phase information. Thus, passive methods that rely on frequency, phase and reactive power cannot be adopted. Islanding states in
DC systems can only be detected by voltage and current information through passive IDMs, but there is a large NDZ when PV source output power matches with local loads during islanding. Therefore, passive methods might not be suitable for DC islanding detection.

Active methods detect islanding operations by injecting disturbances into the system. Disturbance signals quickly destabilize the system after islanding, thereby islanding states can be detected with small (or even zero) NDZs. Active frequency shifting method [20], Sandia frequency shifting method [21], slip mode frequency shifting method [22], active/reactive power disturbance method [23, 24] and impedance measurement method [25] are common active IDMs that applied in AC system. However, due to the characteristics of DC systems, various types of frequency shifting methods and reactive power disturbance methods cannot be applied.

At present, the research on DC islanding protection mainly relies on AC active IDMs. Literature [26] proposes an IDM based on the switching state of DC circuit breakers, but the method only studies a specific single-PV system. Its performance might be poor for a multi-terminal system with a large number of switches. In [27], a positive feedback current perturbation method is proposed. Positive feedback disturbances rapidly expand the power mismatch after islanding and this makes the DC islanding easy to be detected. In [28–30], voltage positive feedback methods based on current and power disturbance are applied to DC islanding detection. The influences on dynamic response, stability margin and impedance characteristics are analyzed. However, literature [27–30] only validates IDMs in single-PV grid-connected system. Literature [31] presents an active method based on the DC/DC injection. The islanding detection scheme is formed by estimation of the difference of high frequency impedance before and after the islanding. The method presented [31] does not rely on additional injection unit, and the high frequency impedance that was used as the basis of judgment changes significantly. However, this method takes the single-unit system as the premise and does not discuss the performance of the multi-unit system.

It has been pointed out that in a multi-PV AC distribution system, the attenuation effect will affect the detection efficiency of power disturbance methods [25, 30]. In a multi-terminal DC system, injected signals can be distorted and diluted by the increase of system capacity as well. Scattered low-intensity disturbances may lead to increased detection time and even result in detection failure. Due to the difference of electrical parameters of variable DC/DC converters, it is difficult to realize synchronous injection within multi-converters. Therefore, power disturbance methods are difficult to be applied in a multi-terminal DC system.

In order to address the above presented issues, this paper proposes an impedance measurement IDM. The main contributions of this paper are: (1) The method uses high-frequency harmonic impedance as the main criterion to detect islanding state. Its calculation requires less disturbance intensity, which can avoid the attenuation effect of multi-converter injection. (2) The method chooses harmonic voltage as an auxiliary criterion to accurately identify complex islanding states. (3) With a time delay and a current auxiliary criterion, the islanding can be effectively distinguished from system short circuit faults. Simulation results validate that the proposed IDM can accurately identify multiple islanding states in a multi-PV flexible DC power distribution system considering the system transient disturbances.

2 HIGH-FREQUENCY HARMONIC INJECTION METHOD BASED ON DC/DC CONVERTERS

With reference to DC demonstration projects in China, a multi-terminal flexible DC distribution system is built as a test bench system as shown in Figure 1. Four groups of PV sources and DC loads are connected to the DC system through DC/DC converters, and the DC system is connected to the AC grid via two MMCs. Smoothing reactors are equipped on the outputs of these converters to limit the DC fault current to an acceptable value for the converters. Circuit breakers of the branches in Figure 1 are indicated by K3–K6. Circuit breakers on the lines are indicated by B12–B61.

When a large disturbance or fault occurs in the system, PV sources and DC loads may form an islanding operation state due to the tripping of circuit breakers. In a multi-PV DC system, it is difficult to achieve synchronous injection of active power disturbances, therefore the detection accuracy of active injection IDMs can hardly be guaranteed. The occurrence of islanding state changes the structure of the system, which will cause a significant change on the impedance of the system and islanding state can be detected accordingly. Accurate measurement of the system impedance requires a harmonic source with a constant frequency. In this paper, DC/DC boost converters are used to inject high-frequency harmonic disturbances, so impedance of the system can be measured without additional injection sources.

The structure of a DC/DC boost converter consists of multiple submodules. As shown in Figure 2, the inputs of the submodules are connected in parallel and the outputs are connected in series to increase the output voltage of the converter. In Figure 2, \( C_L \) and \( C_H \) are regulator capacitors of low and high voltage side. The \( r_{dc} \) is the output voltage of a single submodule.

The frequency of characteristic harmonics of the output voltage by the uncontrolled rectifier are even multiples of the frequency of its input voltage [32]. Therefore, the frequency of characteristic harmonics of the DC/DC boost converter are even multiples of the converter’s carrier frequency.

When performing the harmonic injection, the H-bridge in one submodule of the converter is intermittently blocked. The frequency of this blocking is set to the carrier frequency of the converter, which is recorded as \( f_s = 1/T_s \). The duty ratio of this blocking is recorded as \( k \). During the blocking, the output voltage of the high-frequency transformer in this submodule will be reduced to zero. Therefore, the blocking can be equivalent to injecting a square wave with the amplitude of \( -2r_{dc} \), the frequency of \( f_s \), and the duty ratio of \( k \) in the output voltage of
the high-frequency transformer in this submodule. The Fourier expansion of this square wave can be expressed as:

\[ f(t) = -k u_{dc} + \sum_{n=1}^{\infty} a_n \cos \left( 2n\pi f_s t \right) \]  

(1)

where \( a_n \) is the amplitude of \( n \)-th harmonic, which can be expressed as:

\[ a_n = \frac{2}{T} \int_{-kT/2}^{kT/2} f(t) \cos(2n\pi f_s t) dt = -\frac{2 u_{dc} \sin(n\pi k)}{n\pi} \]  

(2)

It can be known from Equations (1) and (2) that the injected square wave contains harmonics whose frequencies are integer multiples of the converter’s carrier frequency. The amplitudes of the harmonics are negatively correlated with their frequencies. The harmonic of the carrier frequency \( f_s \) has the highest amplitude and it does not overlap with characteristic harmonics of the DC/DC boost converter. Therefore, the measurement of high-frequency impedance of the DC system is based on the injected harmonic of frequency \( f_s \). To prevent the interference between the high-frequency harmonics injected by different DC/DC converters, when multiple DC/DC converters are used as injection sources, their injection periods should not overlap.

3 ISLANDING DETECTION METHOD BASED ON IMPEDANCE MEASUREMENT

3.1 Basic principle of impedance measurement method

Based on the high-frequency harmonics injected through DC/DC boost converters, high-frequency impedance of the system can be accurately measured. In order to explain the basic principle of the impedance measurement IDM, the impedance model of the multi-terminal flexible DC distribution system is shown in Figure 3.

In Figure 3, DC/DC boost converter of PV3 is used as the harmonic injection source. DC voltage and current are measured at the measuring point shown in Figure 3 and the high-frequency impedance of the system can be calculated by...
Fourier algorithm. For the convenience of description, only the impedance model of node 2, 3 and 4 in Figure 1 are shown in Figure 3.

The islanding state of PV3 and DC load 3 is taken as an example to describe the change of the high-frequency impedance. After PV3 and its DC load entered islanding state, the impedance of the islanding subsystem in Figure 3 measured at the measuring point can be expressed as:

$$Z_{\text{Island}} = Z_{\text{load3}} + 2 \times X_L$$  \hspace{1cm} (3)

where $Z_{\text{load3}}$ is the impedance of the DC load $R_{\text{load3}}$ and its DC/DC buck converter. The $X_L$ is the inductive reactance of one smoothing reactor.

The measured impedance when PV3 and its DC load are connected to the DC grid is the parallel value of $Z_{\text{Island}}$ and the impedance of the rest of the DC system. The grid-connected impedance $Z_{\text{Grid}}$ can be expressed as:

$$Z_{\text{Grid}} = Z_{\text{Island}} \parallel Z_0$$  \hspace{1cm} (4)

where $Z_0$ is the impedance of the DC distribution system except PV3 and DC load3. \hspace{1cm} $\parallel$ means that two impedances are connected in parallel.

The series reactance component $X_L$ in $Z_{\text{Island}}$ shows a high impedance value at high frequencies. $Z_0$ is consisted of multiple parallel branches whose structures and compositions are similar to $Z_{\text{Island}}$, so the high-frequency impedances of $Z_0$ is significantly smaller than $Z_{\text{Island}}$. That is, there is a large difference between the high-frequency impedance values before and after islanding. Through this impedance difference, islanding operation states including a single PV unit can be accurately detected. Considering that reactance value is high at high frequencies, the measured reactance value is selected as the characteristic quantity of the proposed IDM.

However, when there are multiple sets of PV sources connected in the DC system, islanding operation states that contain multiple PV sources may be formed. For example, the tripping of circuit breaker B32 and B45 in Figure 1 may cause PV3 and PV4 with their loads to enter a multi-unit islanding state. Such complex islanding states can hardly be detected by the above-mentioned impedance changes alone.

### 3.2 Multi-unit islanding detection method considering harmonic characteristics

When a multi-unit islanding operation state occurs, the DC system can be divided into an islanding subsystem and a grid-connected subsystem. Islanding subsystems formed by different PV units have similar structures. This structural results in similarities in their measured impedance. Table A1 in the Appendix shows the measured reactance values of the islanding subsystems of all possible islanding conditions in the system shown in Figure 1. The four rows in the table are high-frequency reactance values measured at measuring points of PV3 to PV6. As shown in the table, the difference in the measured reactance of islanding subsystems of different multi-unit islanding states are relatively small.

Therefore, it is difficult to set thresholds separately for all possible multi-unit islanding conditions by the high-frequency reactance alone. In this paper, the amplitude of the injected harmonic voltage is used as an auxiliary criterion to identify the PV units that included in islanding operation states. The injection frequency of all harmonic sources (the carrier frequency of DC/DC boost converters) in the system are set to the same frequency. Their injection periods are evenly distributed in one injection cycle and do not overlap with each other. MMC will not be included in islanding subsystems. In this case, the voltage of the injection frequency is measured at the DC port of MMC. When some PV units enter an islanding state, the amplitude of harmonic voltage in their corresponding injection period will be significantly reduced, and the islanding PV units can be accurately identified.

To be specific, take the system shown in Figure 1 as an example, time-sharing harmonic injection for each unit ensures that the harmonic injection period does not overlap. During normal grid-connected operation, the reactance measured should be less than $X_{\text{th0}}$ (the threshold of grid-connected state), at the same time, the measured harmonic voltage of MMC1 should all be non-zero value. Suppose PV3 unit suddenly occurs the islanding, the measured reactance value of PV3 unit should be greater than $X_{\text{th1}}$ (the threshold of single-unit islanding state), while the measured reactance value of other units should be greater than $X_{\text{th0}}$ which shows a unit occurs the islanding. In order to ensure the accuracy of the judgment results, the harmonic voltage at MMC1 is added as the auxiliary criterion.
When the PV3 occurs the islanding, the corresponding harmonic voltage value in the injection period shall be significantly lower than that in other periods. It means that PV3 is islanding.

### 3.3 Threshold setting of the islanding detection method

To identify whether there are islanding operations in the system, the threshold of grid-connected state is set to:

\[ X_{\text{th0}} = 1.10 \times X_{\text{Grid}} \]  \hspace{1cm} (5)

where \( X_{\text{Grid}} \) is the theoretical reactance value when no islanding operation occurs in the system. \( X_{\text{Grid}} \) may be different when measured at measuring points of different PV units. The occurrence of islanding operations reduces the number of parallel branches in the system, so the measured reactance value at all measuring points after islanding will be increased. Equation (5) indicates that when the measured reactance value exceeds 110% of \( X_{\text{Grid}} \), it is considered that there is an islanding operation in the system. Whether the measuring point is included in the islanding subsystem or not, all forms of islanding operations will increase the measured reactance value. Therefore, \( X_{\text{th0}} \) only detects the existence of islanding states in the system. It cannot accurately judge the number of PV units included in the islanding state.

To identify the number of islanding PV units, the threshold of single-unit islanding \( X_{\text{th1}} \) is defined as:

\[ X_{\text{th1}} = X_{\text{Grid}} + k_{\text{th}} (X_{\text{Island}} - X_{\text{Grid}}) \]  \hspace{1cm} (6)

where \( X_{\text{Island}} \) is the theoretical value of the harmonic reactance measured in the single-unit islanding state. The number of paralleled branches in the single-unit islanding subsystem is the smallest among all possible islanding states (no parallel branch), so the measured reactance of the single-unit islanding subsystem has the highest value. The \( k_{\text{th}} \) in Equation (6) is a sensitivity coefficient. Considering the calculation error that may occur in practice, \( k_{\text{th}} \) is set to 0.9 in this paper. When the increment of the measured reactance exceeds 90% of the theoretical difference between the reactance of single-unit islanding and the grid-connected condition, it is considered that this PV unit enters a single-unit islanding state.

When the measured reactance of all measuring points exceeds \( X_{\text{th0}} \) but does not exceed \( X_{\text{th1}} \), it is considered that there is a multi-unit islanding state in the system. In this case, the amplitude of the injected harmonic voltage in the injection period of islanding PV units will drop to near zero. Considering the transient disturbances and measurement error, when the amplitude of the injected harmonic voltage is lower than 10% of its lowest amplitude in grid-connected state, it is considered that the corresponding PV units are involved in the islanding subsystem. The flow chart of the proposed detection method is shown in Figure 4.

In order to prevent the actual measured impedance from approaching or slightly exceeding the judgment standard, an auxiliary judgment is proposed, that is, the method mentioned in the paper is started only when the continuous measured impedance values within 1 s all exceed the judgment threshold, and the islanding is considered to occur, otherwise the method is blocked.

### 3.4 A method for distinguishing the islanding from short circuit faults

Since the islanding detection scheme proposed in this paper is based on the impedance variation at high frequencies, and the high-frequency impedance varies with the network structure, the proposed method may have problems when the network structure changes due to short circuit fault.

To solve the problem, we should find out the differences between the islanding and the short circuit fault. First of all, it will not cause severe damage to system after a short time of the islanding, and the islanding detection time is within 2 s. For short circuit faults, it will cause very severe damage to the network and the fault clearance time is normally within 10 ms. The operating time differences between islanding protection and system disturbances (faults) protection can be used to distinguish the non-islanding situation (by adding a small-time delay in the islanding protection). In addition, due to the fact that the islanding in general will not have very large over-current as short circuit fault, current changes before and after the impedance variations can be used as a threshold to prevent malfunction of the islanding detection method during faults.

In summary, short circuit protection and the islanding protection are all equipped in the network with different protection
schemed and thresholds. For short circuit faul the line protection device can detect the current or ratio of current enlargement during a fault and trip the breakers with no time delay regardless of islanding/non-islanding operation. The faults will be cleared within 10 ms. For islanding cases, the over-current cannot meet the line protection starting threshold. The islanding protection will estimate the high frequency impedance and sends the tripping signal after a delay of 1 s.

4 \hspace{1em} HIGH-FREQUENCY IMPEDANCE MODEL OF DC CONVERTERS UNDER HARMONIC DISTURBANCE

In order to set thresholds of the proposed IDM, the high-frequency impedance models of DC converters in the DC distribution system need to be established. The specific high frequency impedance model of DC/DC converter and MMC is given in the literature [31], which is briefly introduced below.

4.1 \hspace{1em} High-frequency impedance model of DC/DC converters

There are two types of DC/DC converters in the DC system. The DC/DC boost converter connects PV sources to the DC grid, and its topology is shown in Figure 2. The DC/DC buck converter connects DC loads to the DC grid. Its topology is shown in Figure 5. The connection structure of the submodules of the two types of converters are the same, but the circuits of the input and output sides of the submodules are opposite.

According to the harmonic injection method proposed in Section 1.2, the amplitude of the injected high-frequency harmonics do not exceed the amplitude of the output voltage of one submodule. Therefore, the conduction state of the diodes in the submodules is still controlled by the H-bridge under harmonic injection. For the convenience of analysis, it is assumed that the on-resistances of both IGBTs and diodes in submodules are equal. In this case, the conduction paths of the injected high-frequency harmonics in two types of DC/DC converters are the same. Taking the submodule of DC/DC boost converter as an example, the paths of the injected high-frequency harmonics are shown in Figure 6.

Controlled by the H-bridge, there are two different conduction paths of the injected harmonics. As can be seen in Figure 6, the electrical components on the two paths are identical. Therefore, two harmonic paths can be considered as the same case for impedance analysis. Replacing the high-frequency transformer by the T-type equivalent circuit and reducing all the components in the submodule to its high-voltage side, an equivalent impedance model can be obtained as shown in Figure 7.

In Figure 7, \( r_1, r_2, r_0 \) and \( L_1, L_2, L_{m2} \) are resistance and reactance of primary side, secondary side and the excitation loop of the high-frequency transformer in the submodule. \( a \) is the transformer ratio. \( I_1, U_1, I_2, U_2 \) are currents and voltages of the input and output ports. This two-port impedance model can be...
The impedances of the three branches containing inductance in Figure 6 are recorded as:
\[
Z_1 = a_{22}^* r + jX_{L1}, \quad Z_2 = r + jX_{L2}, \quad Z_3 = a_{11}^* jX_{L12}. \tag{9}
\]

The capacitive reactance of \(C_H\) and \(C_L/a_{22}\) are recorded as \(Z_{CH}\) and \(Z_{CL}\). Then the parameters in matrix \(G\) can be expressed as:
\[
G = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \tag{7}
\]
\[
\begin{align*}
I_1 &= g_{11} U_1 + g_{12} I_2 \\
U_2 &= g_{21} U_1 + g_{22} I_2
\end{align*} \tag{8}
\]

4.2 High-frequency impedance model of MMC

The structure of MMC is shown in Figure 8. Each bridge arm of MMC is composed of multiple submodules and an inductance in series. In this paper, half-bridge submodule is taken as an example for high-frequency impedance analysis of MMC. The structure of the half-bridge submodule is given on the right side of Figure 8. When a submodule is cut off, the harmonics injected form the DC port of MMC only flow through the switch tube in the submodule. When the submodule is in the input state, the injected harmonics will flow through the switch tube and the capacitor.

Figure 8 can be reduced to an RLC series-parallel circuit as shown in Figure 9(a). In Figure 9(a), \(L_0\) is the bridge arm inductance, \(R_{arm}\) is the sum of the on-resistance of the switch tubes on one bridge arm, and \(C_0\) is the capacitor of one submodule. The number of submodules input on the bridge arm \(k (k = p, n, \text{representing the positive and negative bridge arm respectively})\) of phase \(r (r \text{ stands for A, B, C})\) in Figure 9(a) is denoted as \(n_{kr}\).

The number of submodules in the input state on each bridge arm is time-varying. However, the sum of input submodules on the two bridge arms of the same phase is always constant, that is:
\[
n_{pr} + n_{nr} = N \tag{14}
\]

where \(N\) is the number of submodules on one bridged arm. So the impedance of one bridge arm can be expressed as:
\[
Z_{pr} = R_{arm} + j\left(\omega L_0 - \frac{n_{pr} \omega C_0}{N - n_{pr}}\right) \tag{15}
\]

\[
Z_{nr} = R_{arm} + j\left(\omega L_0 - \frac{n_{nr} \omega C_0}{N - n_{nr}}\right)
\]

Considering that the inductive reactance at high frequencies will be much larger than the capacitive reactance, Equation (15)
can be:

\[ Z_{pr} \approx Z_{nr} \approx R_{arm} + j\omega L_0 \]  (16)

In Figure 9(a), the red line shows the flow path of the high-frequency harmonics injected form the DC port between A and B phases. The four bridge arms in the flow path form a Wheatstone bridge. It can be known from equation (16) that the high-frequency impedances of the four bridge arms of the Wheatstone bridge are approximately equal. So the Wheatstone bridge is balanced at high frequencies. High frequency harmonics injected from the DC side will not flow into the AC side through bridge arms of MMC. For any two phases of MMC, this conclusion can be established. Therefore, when harmonics are injected from the DC side, the equivalent impedance model of MMC will not include the AC grid or any other AC components.

Considering the relationship given by equation (14), the circuit shown in Figure 9(a) can be further simplified into a series circuit as shown in Figure 9(b). The high frequency impedance model of the MMC in Figure 9(b) can be expressed as:

\[ Z_{MMC} = \frac{2}{3} R_0 + j\omega \left( \frac{2}{3} L_0 - \frac{N}{3C_0} \right) \]  (17)

5 | SIMULATION VERIFICATIONS

5.1 | Verification of the accuracy of the impedance models

Since the paper is time-sharing harmonic injection, there is only one harmonic source at most at any time. The original system is simplified as the Figure 10:

Since the DC voltage can be considered stable, proving the stability of the system is equivalent to proving the stability of the DC current, according to the equation:

\[ U_{dc} = I_{dc} \times (Z_{MMC} \parallel Z_{PV} \parallel Z_{load}) \]  (18)

If we want to prove the stability of \( I_{dc} \), according to the reference [33], it can be converted to prove the stability of impedance. The Nyquist curve of the equation is shown in the Figure 11, it can be seen that the curve does not pass the point (-1, j0), and the system is a stable system.

5.2 | Verification of the accuracy of the impedance models

A simulation model of the flexible multi-PV DC distribution system in Figure 1 is built in PSCAD/ETDMC to verify the
proposed algorithms. The rated voltage of this DC system is \(\pm 10 \text{kV} \) (20 kV). The rated output power of all PV sources is 2 MW. The carrier frequency of DC/DC converters in the system is 3 kHz. That is, the frequency of the injected disturbance harmonic is 3 kHz. Four DC/DC boost converters take turns to perform harmonic injection in a cycle of 0.5 s. The length of the injection of one converter is 0.125 s. DC loads in the simulation model are fully matched with the output of the PV sources. The smoothing reactors at the high-voltage side of converter are 10 mH. Transmission lines adopt \(\pi\)-shaped equivalent impedance model in the simulations. The length of the transmission lines between each node are 1.75 kM. The impedance of other lines is ignored. Detailed parameters are listed in the Appendix and shown in Table A1, Table A2, Table A3, Table A4 and Table A5.

To verify the accuracy of the proposed impedance models of DC/DC converters and MMC, circuit breaker B21 and B34 are opened to form a subsystem that contains only MMC2 and PV3. The DC/DC boost converter of PV3 works in normal condition and does not adopt the proposed harmonic injection method. An external harmonic source is used to inject 10–4000 Hz disturbance harmonics with an interval of 10 Hz into the subsystem. The theoretical and measured values of the impedance of the DC/DC boost converter and the MMC in the subsystem are shown in Figures 12 and 13.

For the convenience of observation, the theoretical and measured values of 0–50 Hz in Figure 12 and 0–150 Hz in Figure 13 are enlarged. As shown in Figure 12, the difference between theoretical and measured impedance values of the DC/DC boost converter is small at 10–4000 Hz frequency range. The maximum error does not exceed 3%. Figure 13 shows the theoretical and measured values of the impedance of MMC2. Since Equation (16) can only be established at high frequencies, there is a relatively large error in 10–150 Hz frequency range. However, the impedance model has high accuracy at the frequency range of above 150 Hz, and the maximum error does not exceed 5%.

In summary, simulation results show that the impedance models can offer accurate and constant values in the high frequency range, which can meet the requirements of impedance calculation and threshold setting of the proposed IDM.

5.3 Verification of islanding detection

Constant power loads are mainly connected to the grid with power electronics converters and switches etc. In the DC network system, the constant power loads are connected to the DC grid with AC/DC converters and DC/DC converters, and the constant impedance value of these two types of converters are shown in the paper. The high frequency harmonics will not enter the AC grid/loads and PVs/load as analyzed previously in the paper. In this case, the load types, AC power grid and the PV operation states will not affect the accuracy of the proposed method.

5.3.1 Simulations of single-unit islanding operations

Single-unit islanding simulations are performed on PV3 and PV4 units. The reactance value measured at PV3 and the amplitude of 3 kHz harmonic voltage measured at MMC1 are shown
in Figure 14. In Figure 14, the system enters islanding operation state at 3 s. In order to compare the difference between the measured and theoretical values of the reactance before and after islanding, the system continues to operate in islanding state. The startup time (0–1 s) is not drawn in the figures.

Figure 14(a,b) show the measurement results of the single-unit islanding of PV3. In Figure 14(a), $X_{th1}$ is marked with a gray dotted line. The harmonic reactance shows a significant change at the moment of entering islanding state. The PV3 single-unit islanding can be correctly detected by the threshold $X_{th1}$.

Figure 14(c,d) show the measurement results of the single-unit islanding of PV4. After islanding, the reactance value measured at PV3 exceeds $X_{th0}(76.59\,\Omega)$ but does not exceed $X_{th1}(316.33\,\Omega)$. However, the harmonic amplitude during the injection period of PV4 is reduced to approximately zero. That is, the islanding PV unit can be effectively identified by the amplitude of 3 kHz harmonic voltage.

In Figure 14(a,c), the system enters islanding state at 3 s, but at this time the previous injection period of PV3 has already ended. The next injection period is 3–3.125 s, therefore the next measured reactance value is given at 3.125 s. Since four of the DC/DC boost converters in the system inject harmonics in turn of 0.5 s, the islanding detection would have a delay of up to 0.5 s. However, this delay does not exceed the limit imposed by the relevant regulations on islanding detection time.

5.3.2 Simulations of multi-unit islanding operations

Figure 15 shows the high-frequency reactance measured at PV3-6 unit and the 3 kHz harmonic voltage measured at the DC port of MMC1 before and after the multi-unit islanding states of PV3 and PV4.

Due to the intermittent injection strategy, the time of the reactance changes obtained by four measuring points are different. The theoretical value of the high-frequency harmonic reactance and the grid-connected threshold $X_{th0}$ are also different for different measuring point due to their different locations in the DC system. All the measured reactance values exceed the grid-connected threshold $X_{th0}$ in an injection period of 0.5 s after islanding. However, the measured reactance at all measuring points did not exceed the single-unit islanding threshold $X_{th1}$. So, it is considered that a multi-unit islanding state occurred in the system. It can be known from Figure 15(e) in which the harmonic voltage values of PV3 and PV4 units are significantly reduced. Therefore, the islanding state containing PV3 and PV4 units can be detected.

Figure 16 shows the harmonic reactance measured at PV3 and the harmonic voltage measured at MMC1 under multi-unit islanding operation states of PV45, PV345, PV456 and PV3456. Under the above four different multi-unit islanding conditions,
**FIGURE 15** Measured reactance and injected harmonic value in the multi-unit islanding state of PV3 and PV4

(a) Measuring reactance measured by PV3

(b) Measuring reactance measured by PV4

(c) Measuring reactance measured by PV5

(d) Measuring reactance measured by PV6

(e) 3kHz harmonic measured by MMC1

**FIGURE 16** Measured reactance and injected harmonic value of different multi-unit islanding states
the proposed IDM can achieve accurate calculation of measured reactance values, and the error does not exceed 6%. Islanding units can be accurately identified through the combination of reactance thresholds and the amplitude of 3 kHz harmonic voltage.

5.3.3 | Simulations of transient disturbances

To test the proposed IDM in transient disturbance conditions, the following simulations were performed in the grid-connected system: the voltage fluctuations of the DC grid, the fluctuations of output power of PV3 unit and the fluctuations of DC load3. DC voltage, DC load3 and active output of PV3 all vary from 1.4 to 0.6 times the rated value with an interval of 0.2 times. The change of the measured reactance at the measuring point of PV3 and other relevant electrical parameters are measured as shown in Figure 17. The impedance of DC load3 in Figure 17(f) is reduced to the high-voltage side of its DC/DC buck converter.

In Figure 17, the fluctuations in the simulations have not significantly affected the proposed IDM. The error of the measured harmonic reactance can be kept within 5% and does not exceed $X_{th0}$ under the three disturbances. That is, the proposed IDM will not malfunction under the above transient disturbance conditions.

5.3.4 | The experimental test

In the simulation, we have verified the high-frequency impedance model of DC/DC, the high-frequency impedance model of MMC, and the islanding detection method when a single unit or multiple units occur the islanding. The verification results are consistent with the theoretical deduction.

To test the calculation accuracy of the method and the operation time of the islanding protection, the test was carried out on the “general protection and control experimental platform” as shown in the Figure 18. The test platform consists of RTDS simulation system and general protection and control experimental platform that consists PSD signal processing boards and FPGA boards. RTDS is used to simulate the photovoltaic DC distribution network, and the general protection and control experiment platform is used to carried out the islanding protection algorithm. The parameters of each component in the test platform are designed according to the existing standards and reference.

The test system consists four parallel photovoltaic units and the rated active power output of a single unit is 2 MW. The local active load and system active power output can be set to be matched. The sampling rate of the platform is set to be 5 kHz. The detection results of the algorithm under the test platform are shown in the Figure 19. The test system enters the islanding operation state at 3 s, then the measured value of harmonic reactance exceeds the setting threshold after 0.5 s. The above calculation and reaction time can meet the requirements of relevant standards for islanding detection.

5.3.5 | Harmonic analysis

As an active method, the paper analyzes the influence of disturbance on the power quality of the system. Since the injected harmonics do not pass through the MMC into the AC grid, the
FIGURE 18  Physical layout of the experimental test bench

FIGURE 19  Islanding detection signal in the test bench

effects will be limited in the DC network. In the single-machine grid-connected system, the frequency harmonic components of the system before and after harmonic injection are calculated, and the comparison diagram of the frequency harmonic content before and after harmonic injection is drawn as shown in Figure 20. The red dotted line is the content of each voltage harmonic measured at PV3 outlet without injection, while the blue solid line is the content of each voltage harmonic after injection. Each quantity in the figure is given in the form of per-unit value, and the reference value is the rated DC voltage. For convenience of comparison, the DC component is excluded in the figure.

As shown in Figure 20, when harmonic injection is not carried out, the harmonics in the system are mainly the characteristic harmonic frequency of the DC/DC converter (even frequency 6 kHz, etc.). The harmonic injected by the method is odd times of the carrier frequency of DC/DC converter (3 kHz, 9 kHz, etc.), the voltage harmonic amplitude of the corresponding frequency was increased significantly after injection and it does not overlap with the characteristic frequency of the converter.

FIGURE 20  Harmonic analysis

TABLE 1  Comparative results

| Switch position | Methods used in this paper | Active islanding detection |
|-----------------|-----------------------------|-----------------------------|
| B32, B34        | PV3 is islanding             | PV3 is islanding             |
| B43, B45        | PV4 is islanding             | Unable to detect             |
| B32, B45        | PV34 is islanding            | PV3 is islanding             |
| B43, B56        | PV45 is islanding            | Unable to detect             |
5.4 | Comparison with similar methods

In order to demonstrate the advantages of the islanding detection method proposed in this paper, the published papers that mostly use external injection sources and only single machine is considered are used for comparison. The method used in this paper is compared with the active injection impedance islanding detection method which only applies the injection source at PV3. The control scheme and the injection method used for comparison is similar to the reference [34]. The comparison results are presented in the form of following Table 1:

It can be seen from the results that the islanding detection method of injection only considers the situation of single unit cannot the actual islanding when it occurs in a unit other than the injection source. However, the method used in this paper takes the situation of multiple units into account, and it can be accurately judged no matter where the islanding occurs.

5.5 | Fault condition test

In order to verify the feasibility of the proposed islanding detection during faults, relevant cases were added to the simulation. The PV3 enters islanding at 3 s and a short circuit fault occurs at 4 s, the positions of short circuit faults are at PV3 and PV4 respectively. The Figure 21 shows the measured impedance at PV3 for the two fault conditions when islanding occurs. The Figure 22 shows the characteristic current measured at the PV3 under the two conditions. As shown in the Figure 21(b), when the short circuit fault occurs outside the islanding unit, it will not affect the islanding detection method but when it occurs at the islanding unit (Figure 21(a)) the protection will trip before the islanding. The same situation will happen when fault occurs at a time before 4 s. These figures indicate that faults outside the islanding unit will not cause malfunction of the proposed islanding protection. The faults at the islanding unit will trip the breaker first if the fault occurs within the delay of the 1 s of the islanding detection times.

6 | CONCLUSION

The lack of frequency and reactive power information poses great difficulties for the direct application of most AC IDMs in DC systems. In a flexible DC distribution system with multiple DC/DC converters, the attenuation effect and complex islanding conditions greatly limit the detection accuracy of active power injection methods. Aiming at the islanding detection of multi-terminal flexible DC distribution system, this paper proposes an impedance measurement IDM.
the high-frequency impedance models of DC/DC converters and MMC are established, which provides a calculation basis for the threshold setting of the IDM. Measurement of high-frequency impedance requires less disturbance intensity, so impedance measurement method can avoid the requirement of synchronous disturbance. Each DC/DC converter in the system injects harmonics in turn, and the complex multi-unit islanding conditions can be effectively identified based on the measured reactance and harmonic voltage without using additional injection source. Simulation results show that the proposed IDM can achieve accurate and rapid islanding detection in the flexible DC distribution system and will not be disturbed by transient disturbances.

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### APPENDIX A

#### TABLE A.1 Theoretical values of measured reactance under different islanding conditions

| Grid-connected | PV3     | PV4     | PV5     | PV6     | PV34   | PV45   | PV56   | PV345  | PV456  | PV3456  |
|----------------|---------|---------|---------|---------|--------|--------|--------|--------|--------|---------|
| PV3            | 69.6332 | 378.0027| 87.4787 | 80.4421 | 79.9249| 144.6727| 130.4842| 101.4748| 107.3875| 178.9552| 96.1792 |
| PV4            | 65.3229 | 83.2539 | 378.0027| 81.5966 | 76.1809| 144.6727| 144.6727| 115.7454| 89.4548 | 107.3875| 73.6445 |
| PV5            | 65.3229 | 76.1809 | 81.5966 | 378.0027| 83.2536| 115.7454| 144.6727| 144.6727| 107.3875| 89.4548 | 73.6445 |
| PV6            | 69.6333 | 79.9249 | 80.4421 | 84.4788 | 378.0027| 101.4748| 130.4843| 144.6727| 178.9552| 107.3875| 96.1792 |

*Note: The rows of the table show the results of different measuring points. The columns show the result of different islanding conditions of PV units.*

#### TABLE A.2 Parameters of DC/DC converter

| Parameter                         | Value       | Parameter                         | Value       |
|-----------------------------------|-------------|-----------------------------------|-------------|
| Rated capacity                    | 2.5 MW      | On-resistance of diodes and IGBTs | 0.1 Ω       |
| Carrier frequency                 | 3 kHz       | Low-voltage side capacitor C_L    | 2000 μF     |
| Number of submodules              | 10          | High-voltage side capacitor C_H   | 425 μF      |

#### TABLE A.3 Parameters of high-frequency transformer

| Parameter                     | Value       | Parameter                     | Value       |
|-------------------------------|-------------|-------------------------------|-------------|
| Rated capacity                | 0.3 MVA     | Excitation current            | 1%          |
| Rated frequency               | 50 Hz       | Leakage resistance            | 0.1 p.u.    |
| Rated voltage of high voltage side | 2 kV | Rated voltage of low voltage side | 0.5 kV |