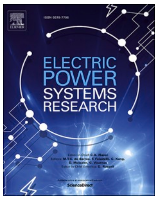
Electric Power Systems Research 231 (2024) 110369

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



A novel voltage arc suppression method for single-phase grounding fault in distribution network based on power router

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ARTICLE INFO

Keywords:
Arc suppression
Distribution network
Grounding fault
Power router
Protection

ABSTRACT

The power-electronized distribution network is the trend with the emergence of widespread adoptions of converters, sparking innovative opportunities for investigating arc suppression. As a future alternative low-frequency transformer, the Power Router (PR) also needs grounding, which can realize arc suppression with well design. Therefore, this paper introduces a novel arc suppression technique for single-phase grounding (SPG) faults in distribution networks directly connected with a PR. Firstly, the distribution network connected with the PR is presented, where the PR operates with grounding in the medium-voltage DC side. Then, the principle of flexible voltage arc suppression through the PR is analyzed, considering the power transfer capability and the impact on circulating current. The multivariable decoupling control under the *dq*0 synchronous rotating frame (SRF) is applied to regulate the zero-sequence voltage, achieving active arc suppression. Furthermore, the article considers various fault conditions and different system-to-ground damping rates. Finally, the simulation results validate the flexibility and effectiveness of the proposed arc suppression method.

1. Introduction

The distribution network is characterized by its large scale, diverse structure, operating in a complex environment, and the fault rate of feeders remains high consistently, seriously affecting the safety and stability of its operation [1,2]. Among the faults in the distribution network, approximately 80 % are single-phase grounding (SPG) faults. If not promptly eliminated or suppressed, these faults can lead to rapid fault propagation, resulting in equipment damage, electrical fires, electric shocks, even widespread and prolonged power outages. Such incidents threaten life and property safety, exacerbated environmental degradation, particularly in regions such as forests, grasslands, cities, industrial and mining areas [3–5]. In recent years, with the rapid development of new power systems, the characteristics of power electronics dominated distribution networks have become more prominent, with more diverse forms. Domestic power systems attach great importance to the rapid disposal of grounding faults in distribution networks. This is critical to prevent grounding faults from reducing power supply reliability [6–9], disrupting continuous electricity consumption, and ensuring the quality of power supply, as well as public safety. Therefore, it is imperative to carry out comprehensive research on arc suppression technologies in sophisticated distribution networks.

According to the different control objectives, the current arc suppression mechanisms for distribution network grounding faults can be categorized into current compensation and voltage suppression. The traditional method of using Arc-Suppression-Coils (ASCs, also known as grounding fault compensation devices in the United States) for arc suppression belongs to current compensation. Since the invention of ASCs by Peterson from Germany in 1916, it has been widely used due to the low cost and simple technology. However, in actual distribution networks, the fault points contain not only reactive power frequency components but also active power components and harmonic components; the current compensation effect of ASCs is limited [10]. Moreover, the grounding parameters vary greatly in urban areas, coal mines, and other power grids. In order to cope with the variations, relevant researchers have successively proposed automatic tracking and adjusting methods for neutral grounding impedance, such as air gap adjustment inductance [11], turn adjustable [12] and magnetic bias [13]

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https://doi.org/10.1016/j.epsr.2024.110369
Received 1 November 2023; Received in revised form 26 February 2024; Accepted 29 March 2024
Available online 4 April 2024

ASCs, high short-circuit impedance transformer [14]. However, the compensation of these methods for active power and harmonic components in fault currents is not sufficient.

In order to solve the problems, experts and scholars have further proposed passive power frequency current compensation and active full-current compensation. The full compensation of passive fundamental current is realized by adding additional bias components. In [15], it proposes a method of neutral point resistance grounding leading phase inductance, neutral point reactance grounding lagging phase capacitance or leading phase inductance. This method needs to adjust the neutral point grounding impedance and the impedance of the bias element at the same time; the operation is slightly complicated. Active full current compensation utilizes an active inverter to inject full current from the neutral point to achieve zero residual current of the grounding fault [16]. Reference [17] proposes a new master-slave ASCs based on the single-phase active filter technology; reference [18] introduces a residual current full-compensation device. They both require high-accuracy online measurements of the zero-sequence currents or parameters to the ground of the distribution network.

Due to the limited effectiveness of current compensation arc suppression and the need for extensive research, experts and scholars have studied voltage suppression arc suppression. The essence of grounding fault arc extinguishing in the distribution network is that the recovery speed of the insulation medium at the fault point is faster than the fault voltage [19]. If the phase voltage of the fault point is consistently suppressed to below the arc reignition voltage, then effective arc suppression of the SPG fault can be achieved [20,21]. Related experts regulate the neutral point voltage through the power electronic voltage source to suppress the fault phase voltage to zero [22], without requiring real-time measurements of zero-sequence currents and ground parameters of the distribution network. A special arc suppression device is proposed in [23], the new neutral point is constructed by full bridge modules, the influences of the line impedance on arc suppression is considered, and the residual voltage compensation is added based on the traditional neutral injected voltage arc suppression. The fault phase transfer technology, which is easy to operate, is introduced in Reference [24]. If the phase selection fails due to unpredictable factors, the SPG fault will become a two-phase grounding fault. The arc suppression of grading voltage regulation intervention through a grounding transformer requires the development of a special transformer, which can flexibly regulate the fault phase voltage by grading and shorting tapping contacts of the special grounding transformer [25].

In line with the development of new energy dominated advanced power systems [26], utilizing existing power electronic equipment in modern distribution networks to handle faults provides new possibilities for arc suppression of SPG faults. Many engineering projects have already been put into operation, such as Xiaoertai hybrid AC/DC distribution systems which uses high-voltage MMC technologies [27]. Reference [28] proposes the utilization of the power router for self-healing of distribution network faults to enhance resilience. Guo et al. [29] proposes a flexible arc suppression method for grounding faults in the distribution network based on three-phase cascaded H-bridge (CHB) grounding, which does not require fault phase selection. In [30], it utilizes three independent arc suppression converters connected directly to three-phase lines of the distribution network, with alternating arc suppression between two non-fault phases. This method requires dedicated compensation converters and measurements of parameters to ground. Reference [31] analyzes the voltage characteristics and zero-sequence current transmission path when the SPG fault occurs in an active AC/DC hybrid distribution network. By preventing the flow of zero-sequence current between converters in the distribution network, the impact on differential protection based on zero-sequence fault current is reduced, but grounding fault arc suppression is not involved.

This article proposes a flexible voltage arc suppression method based on high-voltage stage zero-sequence regulation of the MMC-type power router (MMC-PR) for the modern distribution network with the power router (PR) directly connected. The main contributions of this paper can be summarized as follows:

1) A novel flexible voltage arc suppression method based on the power router is proposed. Since the zero-sequence control of the transformer MMC is limited, the transformerless MMC has been selected as the high voltage stage of PR.
2) A feasible zero-sequence component control strategy is proposed that does not affect the DC bus voltage and reactive power compensation of the PR. And the normal voltage output of the PR ports won't be affected.
3) The derivation of the principle of flexible voltage arc suppression is given through the zero-sequence analysis. Including the analysis of grounding the interpole DC for the zero-sequence injection.
4) An improved $V_{dc}Q$ control adopted by the power router have been proposed. And the implementation of the control and the simulations of SPG arc suppression considering damping impacts based on the high-voltage stage is given in this paper.

The derivation of the principle of flexible voltage arc suppression is given through the zero-sequence analysis of the distribution network with three-stage transformation PR directly connected to the feeder. Using multivariable decoupling control in the *dq*0 synchronous rotating frame (*dq*0 SRF), the zero-axis vector is tracked without a static difference, and the system zero-sequence voltage is adjusted in real-time. Then, the arc suppression of the SPG fault is achieved by the active voltage reduction, and the fault property can be determined. And in order to ensure the applicability of the proposed method, this paper considers various operating conditions, and conducts modeling and simulation analysis, which verifies that the proposed method can realize arc suppression effectively and reliably.

2. Distribution network topology with PR

It is one of the main forms of new distribution networks that power electronic devices such as PR, which are connected to distribution networks. As shown in Fig. 1, three feeders are in the typical distribution network with PR, and $\boldsymbol{E}_A$, $\boldsymbol{E}_B$ and $\boldsymbol{E}_C$ are phase voltages of the three-

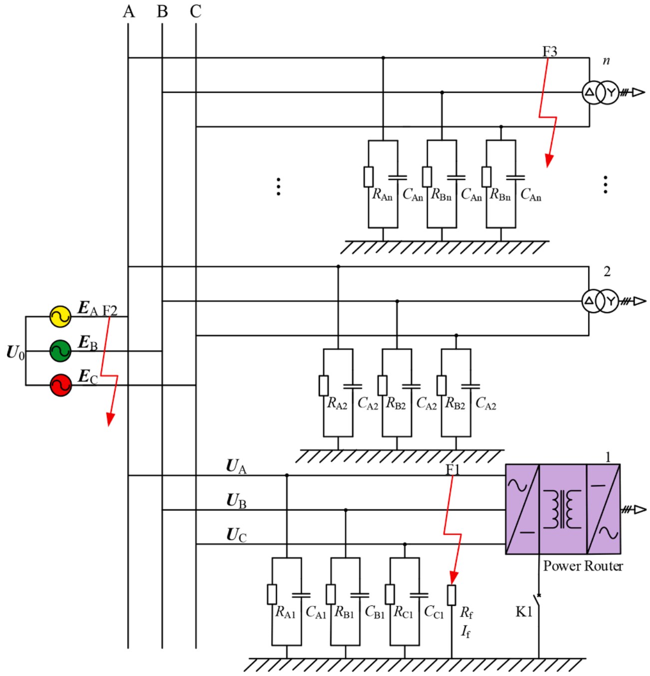


Fig. 1. Typical distribution network topology with PR.

phase power supply. $\boldsymbol{U}_A$, $\boldsymbol{U}_B$ and $\boldsymbol{U}_C$ are the voltages of the three-phase. $\boldsymbol{I}_{AYi}$, $\boldsymbol{I}_{BYi}$ and $\boldsymbol{I}_{CYi}$ are the ground currents of the three-phase lines on the feeder i ($i = 1, 2, 3$). R_{Ai}, R_{Bi} and R_{Ci} are the earth resistances of the three-phase lines on the feeder i ($i = 1, 2, 3$). C_{Ai}, C_{Bi} and C_{Ci} are the earth capacitances of the three-phase lines on the i feeder ($i = 1, 2, 3$). F1, F2, and F3 are three representative grounding fault points located in different lines. R_f is the fault transition resistance of the fault, $\boldsymbol{U}_0$ is the neutral point offset voltage during the SPG fault in the distribution network, and $\boldsymbol{I}_f$ is the fault current. In the topology diagram shown in Fig. 1, there is no connection transformer at the high-voltage side outlet of the PR, which is directly connected to the end of feeder 1; K1 is the control switch for grounding the DC side of the PR.

2.1. Requirements of fault disposal

The safe and stable operation of the distribution network is an important guarantee for sustainable and reliable power supply. As one of the equipment supporting new type distribution networks, the PR should not only have the ability to switch between different operating modes and operate safely, but also have the functions of internal and external fault perception, suppression, isolation and self-protection when accessing distribution network, and manage the power quality, compensate the grid voltage and realize the fault self-healing of the network when needed. At present, the effective suppression or arc suppression of the SPG fault in the 10 kV distribution network is mainly realized by regulating the zero-sequence component. Therefore, the PR contained in the distribution network shown in Fig. 1 is grounded to ensure the zero-sequence current circuit when the fault occurs.

2.2. Topology of PR

The choice of the PR grounding mode is closely related to the topology of its main circuit. At present, the main circuit topology of the PR mostly adopts two mainstream schemes: MMC and CHB. The CHB topology lacks the interface of medium and high-voltage DC, and it is difficult to adapt to the development trend of the AC/DC distribution network. The MMC-PR with high and low-voltage AC/DC ports is more in line with the development of AC/DC power grid in the future, and the modular structure has good flexibility and scalability, which is suitable for high-power applications of medium and high-voltage AC/DC distribution network [32]. It can be used as both a grid-following and a grid-constructing device.

The main circuit topology of the PR is developed from the topology of the solid-state transformer. Considering the power modules losses, the number of modules, the control characteristics and the functional characteristics, it can be concluded that the PR of the three-stage transformation structure has the maximum control flexibility and function scalability [33]. In this paper, the three-stage structure is adopted. As shown in Fig. 2, the three-stage structure has high-voltage AC (HVAC) port, high-voltage DC (HVDC) port, low-voltage DC (LVDC) port, and low-voltage AC (LVAC) port. In order to make the PR easier to achieve redundant control, the high-voltage stage adopts a three-phase MMC topology. And each phase is composed of upper and lower bridge arms (SM_1, …, SM_N) and two bridge arm inductors (L_{ac}) in Fig. 2. Each bridge arm is connected in series with N sub modules, and the number of sub modules is designed according to the voltage level on the high-voltage side [34].

When the high-voltage AC port (HVAC) of MMC-PR is directly connected to the distribution network, in order to make the PR and the distribution network form a zero-sequence circuit during a grounding fault so that it can give full play to the regulatory role in the zero-sequence circuit, a neutral point is set on the MMC-type high-voltage DC side. In Fig. 2, the inter-electrode capacitance grounding is set on the high-voltage DC side of the input stage, and K2 and K3 represent the control switches for the DC-side capacitance grounding, respectively. Of course, the IGBT module can also be connected in series to control the grounding charge and discharge current and voltage properly so as to avoid the impact on the DC side operation when grounding and ensure that the small current grounding property of the distribution network that may be changed does not change by controlling the zero-sequence component of the system. When the SPG fault occurs in the 10 kV small current grounding AC distribution network connected to PR, if PR sets the DC-side grounding, the zero-sequence component of the distribution network system can be flexibly regulated by PR to realize the active and effective arc suppression of the SPG fault and does not affect the operation of the system, which can ensure the continuous power supply when the SPG fault occurs.

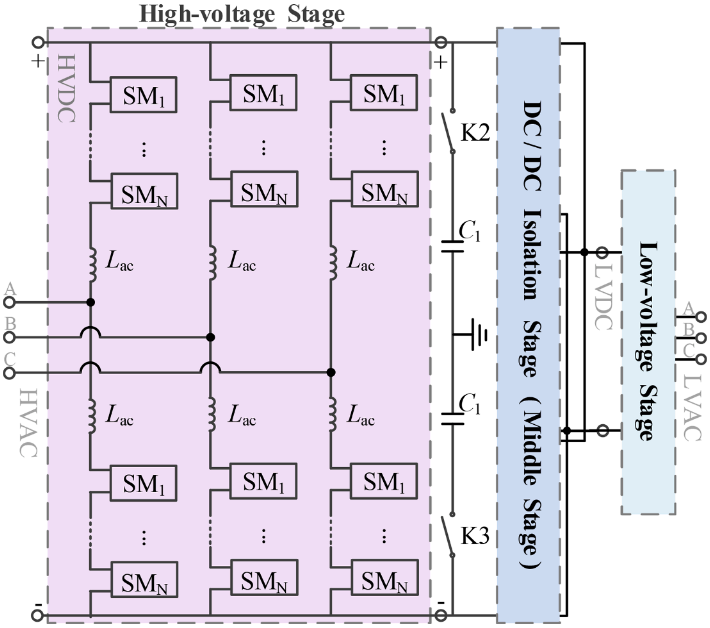


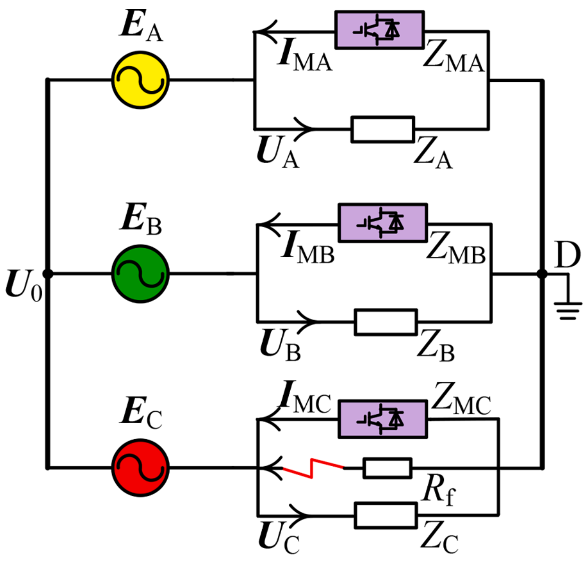
Fig. 2. Topology of MMC-PR with three-stage structure.

3. Principle of proposed arc suppression

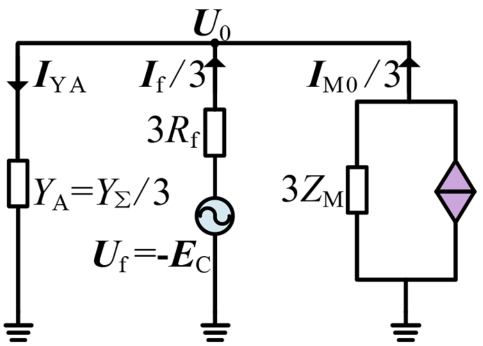
This Section provides an equivalent simplification of the distribution network with PR directly connected, combines with the analysis of the system zero-sequence circuit after a fault, explains the conditions for suppressing SPG faults to arc extinction, and the principle of flexible voltage arc suppression through the directly connected PR.

3.1. Analysis of zero-sequence

When the single-phase grounding fault occurs on phase C in feeder 1 in the distribution network shown in Fig. 1, according to Thevenin's theorem and Norton's theorem, the circuit of the PR high-voltage stage together with the grounding part of the high-voltage DC side can be simplified. In the research of this paper, because the line impedance of the distribution network is small, the influence on the analysis of the proposed method is small, which can be ignored in the analysis process. As shown in Fig. 3(a), the current feeding into the distribution network is selected as the reference direction, and the PR high-voltage MMC is equivalent to the grounding equivalent controlled current source. The corresponding bridge arms are simplified as internal impedance Z_{MA}, Z_{MB} and Z_{MC}, respectively. The zero-sequence current output to the 10 kV distribution network is the grounding equivalent controlled current source of $\boldsymbol{I}_{MA}$, $\boldsymbol{I}_{MB}$, and $\boldsymbol{I}_{MC}$, respectively. The sum of the internal impedance is Z_M, and the sum of the injected zero-sequence current is $\boldsymbol{I}_{M0}$. If the system parameters are set symmetrically, the amplitude of each output zero-sequence current is equal.



(a) Three-phase equivalent circuit



(b) Zero-sequence equivalent circuit

Fig. 3. Equivalent circuit of distribution network in phase C grounding fault.

According to Fig. 3(a), the KCL equation for node D can be obtained as follows:

$$-(Y_A U_A + Y_B U_B + Y_C U_C) = I_{MA} + I_{MB} + I_{MC} + I_f \tag{1}$$

that is,

$$-I_{M0} = (Y_A E_A + Y_B E_B + Y_C E_C) + (Y_A + Y_B + Y_C)U_0 + I_f \tag{2}$$

In (1), Y_A, Y_B and Y_C are the admittance to earth of the distribution network respectively, and $Y_A = 1/Z_A$, $Y_B = 1/Z_B$, $Y_C = 1/Z_C$. $\boldsymbol{U}_0$ is the system zero-sequence voltage, and $\boldsymbol{I}_f$ is the current flowing through the grounding fault branch.

Suppose $Y_A = Y_B = Y_C$, then $Y_A\boldsymbol{E}_A + Y_B\boldsymbol{E}_B + Y_C\boldsymbol{E}_C = 0$. Substitute into Eq. (2), we can get:

$$-I_{M0} = (Y_A + Y_B + Y_C)U_0 + I_f \tag{3}$$

From the above derivation, Fig. 3(a) can be further simplified. From the AC outlet of the PR high-voltage stage, the zero-sequence equivalent circuit of the SPG fault can be equivalent to that shown in Fig. 3(b), where Y_Σ is the total admittance of line to ground, $Y_\Sigma = Y_A + Y_B + Y_C$. $-\boldsymbol{E}_C$ is the virtual power supply voltage at the fault point when the C-phase fault occurs; $\boldsymbol{I}_{YA}$ is the fault phase current to ground. From Fig. 3 (a) and (b), it can be seen that:

$$-I_{YA} = Y_A U_0 = Y_\Sigma U_0/3 \tag{4}$$

At this time, the PR high-voltage stage is equivalent to a controlled current source and forms a zero-sequence circuit of the fault distribution network with admittance to the earth, fault branch, distribution lines, etc. The sum of the current $\boldsymbol{I}_{M0}$ injected by PR to the network is controllable. Considering Eq. (3), regulating $\boldsymbol{I}_{M0}$ can not only avoid the sudden increase of fault current when the SPG fault occurs in the distribution network but also achieve effective arc suppression.

3.2. Zero-sequence voltage regulation

The theoretical arc extinguishing condition of the voltage arc suppression method in this paper is that when the fault point voltage $\boldsymbol{U}_C = \boldsymbol{E}_C + \boldsymbol{U}_0 = 0$, that is $\boldsymbol{U}_0 = -\boldsymbol{E}_C$, the grounding arc is extinguished, and the fault point current is reduced to 0, that is $\boldsymbol{I}_f = 0$, then:

$$-I_{M0} = (Y_A + Y_B + Y_C)U_0 \tag{5}$$

Substituting (4) into (5), it can be seen that:

$$-Y_\Sigma U_0 = 3I_{YA} = I_{M0} \tag{6}$$

That is to say, when $\boldsymbol{U}_C = \boldsymbol{E}_C + \boldsymbol{U}_0 = 0$, i.e., $\boldsymbol{U}_0 = -\boldsymbol{E}_C$, there is:

$$I_{M0} = -Y_\Sigma E_C \tag{7}$$

Therefore, although when Eq. (7) is satisfied, the fault point voltage $\boldsymbol{U}_C$ can also be reduced to 0, it is difficult to accurately measure the parameters to earth of the distribution network; this situation would be more serious when the fault occurs. Since the power source electromotive force of the distribution network is constant, this article proposes to regulate the system zero-sequence component through the MMC-PR so that the zero-sequence voltage of the distribution network is equal in amplitude and opposite in phase to the power source electromotive force. The fault point voltage of the distribution network line is suppressed below the arcing voltage so as to keep the electric field intensity of the weakest point of the fault point lower than the insulation breakdown strength. Thereby achieving the purpose of the arc suppression and effectively preventing the arc reignition, eliminating the fault current, and without requiring measurement of ground parameters.

3.3. Consideration of power transfer capability

Generally, the zero-sequence current is several tens of amperes, and it is related to the distribution network topology and parameters. Therefore, during fault arc suppression, the zero-sequence current flows through the MMC-PR, thus occupying a portion of the power transmission capacity. Assuming the zero-sequence current is 30 A, and the MMC-PR is transmitting 2 MW of active power P, the current in the bridge arm considering the transmission of active power current at this time can be expressed as $I_{\mathrm{dc}} + I_{\mathrm{pac}}$, and I_{dc} is the DC circulating current, I_{pac} is the RMS of arm AC current, there is

$$I_{\mathrm{dc}} = \frac{1}{3}\frac{P}{V_{\mathrm{dc}}} \tag{8}$$

And V_{dc} is the interpolar voltage, U is the effective value of AC voltage, I_{ac} is the AC current, so

$$P = \sqrt{3}UI_{\mathrm{ac}} \rightarrow I_{\mathrm{ac}} = \frac{P}{\sqrt{3}U} \tag{9}$$

$$I_{\mathrm{pac}} = \frac{1}{2}\sqrt{2}I_{\mathrm{ac}} \tag{10}$$

Then the proportion η of the zero sequence current occupying the bridge arm current can be obtained,

$$\frac{I_0}{I_{\mathrm{dc}} + I_{\mathrm{pac}}} = \eta \tag{11}$$

Calculating by substituting the assuming numerical values into Eqs. (8)–(11), the result η indicate that during the fault arc suppression, approximately at most 30 % of the transmission capacity is occupied. Therefore, when designing the MMC-PR, it is necessary to consider an adequate capacity margin. In this paper, the capacity margin of the power router has been fully considered while designing.

4. Implementation and control

This section explains the multivariable decoupling control in *dq*0 SRF is used to track the zero-axis vector without static error, the flexible voltage arc suppression control is realized, and the power allocation control of PR is not affected during arc suppression. After about 150 ms of dissociation, the fault phase voltage would be linearly reduced to determine whether the grounding fault has been eliminated.

4.1. Control of voltage reduction

The precise control of zero-sequence voltage is the guarantee of safe and fast arc suppression. In order to realize the non-static error control of the sinusoidal AC signal, this paper converts the three-phase AC into DC and uses the PID controller to track the sinusoidal signal. Since the SPG fault has little effect on the transmission of PR active power, the converter can increase the zero-sequence component control strategy on the basis of maintaining the original control mode and completing the voltage arc suppression control of the SPG fault.

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} u_{\mathrm{A}} \\ u_{\mathrm{B}} \\ u_{\mathrm{C}} \end{bmatrix} \tag{12}$$

In order to facilitate the regulation of zero-sequence components and meet the transformation requirements of zero-sequence components, it is necessary to further perform the *dq* transformation based on the traditional $\alpha\beta$ transformation. At the same time, a zero axis orthogonal to the $\alpha\beta$ plane is extracted in the $\alpha\beta$ stationary coordinate system. This is achieved by adding a constant row to the Clarke transformation matrix, as shown in Eq. (12). Then, a row of all 1 needs to be added to the Park transformation matrix to achieve the transformation of the zero-sequence component in the three-phase coordinate system to the *dq*0 SRF containing a zero axis through (12) and (13), which can meet the demand of regulating the zero-sequence component in *dq*0.

$$\begin{bmatrix} u_{\mathrm{d}} \\ u_{\mathrm{q}} \\ u_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -sin(\theta) & \cos(\theta) & 0 \\ 1 & 1 & 1 \end{bmatrix} \times \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}\begin{bmatrix} u_{\mathrm{A}} \\ u_{\mathrm{B}} \\ u_{\mathrm{C}} \end{bmatrix} \tag{13}$$

It is easy to obtain that the third row of the transformation matrix is linearly independent of other rows, indicating that the regulation of the zero-sequence component does not affect the positive and negative components. Then, the instantaneous values of three-phase AC voltage at the port of PR connected 10 kV distribution network can be represented by u_{A}, u_{B} and u_{C}, and the instantaneous values of three-phase AC current can be represented by i_{A}, i_{B} and i_{C}. As shown in (12), after the instantaneous values of the three-phase voltages are transformed by the constant amplitude Clarke transformation, further perform the Park transformation as shown in (13), obtaining the values u_{d}, u_{q}, and u_0 in the *dq*0 SRF at the PR port. Among them, u_0 represents the zero-axis voltage, which is the zero-sequence component.

The control target command value $u^*{}_0 = -\varepsilon_{\mathrm{C}}$, among them ε_{C} is the instantaneous value of the power source electromotive force $\boldsymbol{E}_{\mathrm{C}}$ of the C-phase power supply of the distribution network, then there is:

$$u_0^* = -\varepsilon_{\mathrm{C}} \tag{14}$$

Constant DC voltage and reactive power ($\mathrm{V_{dc}Q}$) control is a common control mode for converter devices. In order to effectively track the zero-sequence component of the system with neutral point grounding between DC poles, to achieve accurate zero-sequence component tracking without static error, and not to affect the control of positive and negative sequence components, an improved $\mathrm{V_{dc}Q}$ control structure is given in this paper, as shown in Fig. 4. It can also be clearly seen from Fig. 4 that in the improved control method adopted by the PR high-voltage stage proposed, the control of $\mathrm{V_{dc}}$ and Q has been decoupled from the control of u_0.

$u_{0\mathrm{ref}}$ is the zero-axis voltage obtained after steady-state tracking without static error. After modulation by the PR high-voltage stage, the compensation voltage can be output to regulate the zero-sequence voltage of the system and make it meet $u_0 = -\varepsilon_{\mathrm{C}}$, so as to realize the voltage reduction of the SPG fault in the distribution network. It can be seen from Fig. 4 that the arc suppression control based on the PR high-voltage zero axis does not require additional communication support. As can be seen from Fig. 4, the arc suppression control based on the zero axis of the PR high-voltage stage proposed in this article does not require additional communication support because the power supply radius of the distribution network is not large, the line impedance is small, and the instantaneous value of the generator terminal voltage ε_{C} can be obtained from the PR port voltage. The zero-axis reference value $i_{0\mathrm{M}}$ is obtained by the PID controller to $u_{0\mathrm{out}} + \varepsilon_{\mathrm{C}} = 0$, and the 0-axis voltage reference value $u_{0\mathrm{ref}}$ is generated by the outer-loop controller. After the inverse transformation from the *dq*0 to the *abc* coordinate system, the fault phase voltage is suppressed below the arc reignition voltage, thereby realizing the flexible voltage arc suppression of the SPG fault in the distribution network.

4.2. Implementation aspects

The implementation process of flexible voltage arc suppression of the distribution network with MMC-PR directly connected is shown in Fig. 5.

Through real-time measurement of the zero-sequence component and its variation in the distribution system, PR can determine whether the SPG fault occurs in the distribution network. Based on the grounding

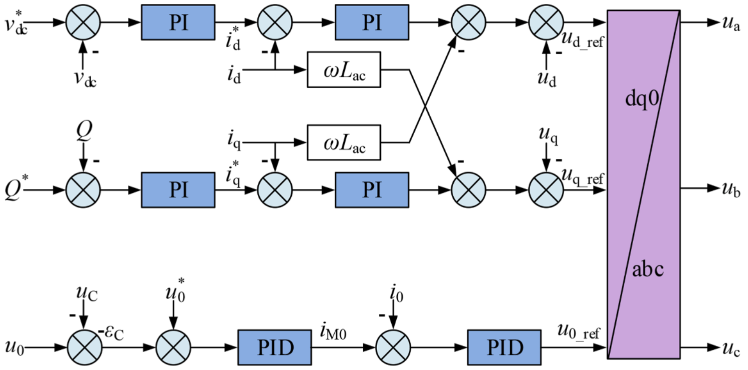


Fig. 4. Control diagram of arc suppression for flexible voltage reduction based on the improved $V_{dc}Q$ controller with zero-sequence control.

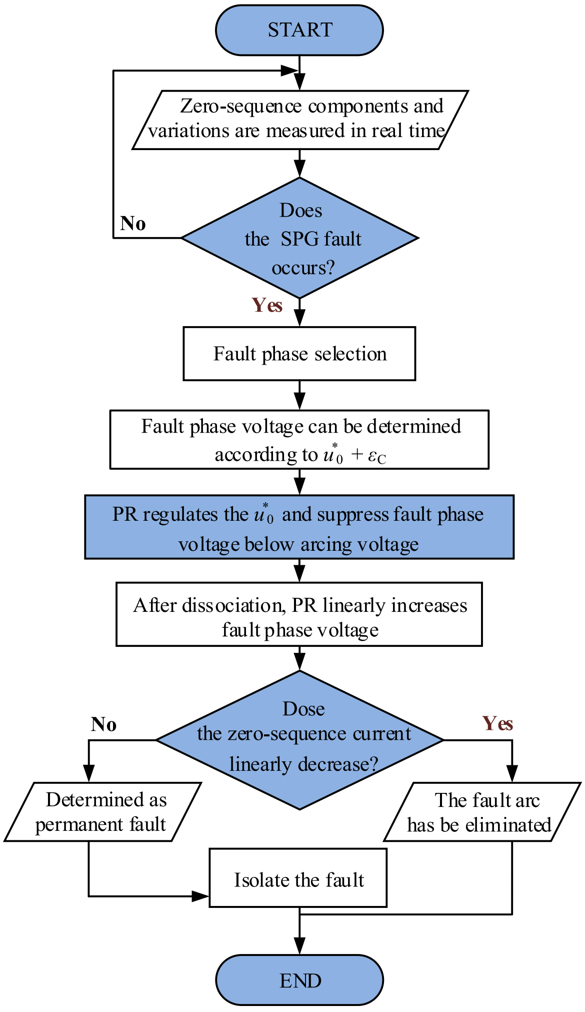


Fig. 5. Process of flexible voltage arc suppression for distribution network based on PR high-voltage stage with the improved $V_{dc}Q$ controller.

mode or compensation degree, the voltage variation value of each phase can be analyzed to determine the grounding fault phase. Based on the selection result, the command value u^*_0 of the zero-sequence voltage of the PR output is determined through the fault phase voltage and zero-sequence voltage, and the arc suppression control based on the *dq*0 SRF is implemented to regulate the system zero-sequence voltage and suppress the fault phase voltage to below the arcing voltage, achieving SPG fault voltage reduction and arc suppression. Refer to the automatic reclosing and consider the withstand capacity of the converter, after about 150 ms of dissociation, PR gradually linearly raises the fault phase voltage by linearly changing the zero-sequence voltage instruction value and detects whether the zero-sequence current of the system linearly changes with the control instruction value. In this way, the nature of the SPG fault is determined. If the system's zero-sequence current changes linearly with the command value, it is judged as a transient SPG fault, and PR withdraws from the flexible arc suppression control. If it changes nonlinearly, it is judged as a permanent SPG fault, and the grounding fault arc may reignite, which can further determine the fault feeder and isolate the fault.

4.3. Impact on circulating current

When the SPG fault occurs, the phase voltage of the faulty phase will decrease. During the arc suppression, the fault phase voltage will be further regulated to zero, and the non-fault phase will further rise to the line voltage. At this time, the DC circulating current component can be used for MM-PR phases balance control, so the circulating current of the MMC will be affected during the fault and the arc suppression. However, arc suppression control is generally invested for a short period of time. Although it will affect the distribution of circulation to a certain extent, the maximum amplitude of circulation will not exceed the designed current withstand limit. Moreover, as shown in Fig. 5, if the AC line has a permanent fault or the arc suppression fails, the power grid automation and relay protection system will be activated, and the fault will be isolated, resulting in a power outage on the fault line, so the corresponding PR port will be blocked. There will be no circulation issues. Therefore, the impact of arc suppression on the circulating current will not affect the operation of the PR or damage components.

For a neutral ungrounded system 10 kV AC distribution network, during the SPG fault, MMC-PR injects zero-sequence current into the grid, causing the system zero-sequence voltage to be opposite to the fault phase power supply electromotive force. Taking the SPG of phase A as an example, the unbalanced voltage of the 10 kV AC system at the time can be expressed as:

$$\begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = \begin{bmatrix} u_{sa}^{+} + u_0 \\ u_{sb}^{+} + u_0 \\ u_{sc}^{+} + u_0 \end{bmatrix} = U_s \begin{bmatrix} 0 \\ \sin\left(\omega t - \dfrac{2\pi}{3}\right) - \sin(\omega t) \\ \sin\left(\omega t + \dfrac{2\pi}{3}\right) - \sin(\omega t) \end{bmatrix} \tag{15}$$

Where, u_{sa}, u_{sb}, u_{sc} is the three-phase voltages of the AC port, equal to u_A, u_B, u_C and the other variables are the same, u_{sa}^+, u_{sb}^+, u_{sc}^+ is the positive sequence voltage, and U_s is the peak value of the phase voltage.

For grid-side currents, negative sequence current suppression control is generally adopted. As a result, the AC port of the MMC-PR primarily contains positive sequence current i_{sa}^+, i_{sb}^+, i_{sc}^+ and zero sequence current i_0, which can be expressed as:

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} i_{sa}^{+} + i_0 \\ i_{sb}^{+} + i_0 \\ i_{sc}^{+} + i_0 \end{bmatrix} = I_s \begin{bmatrix} \sin\left(\omega t + \theta_i^{+}\right) \\ \sin\left(\omega t + \theta_i^{+} - \dfrac{2\pi}{3}\right) \\ \sin\left(\omega t + \theta_i^{+} + \dfrac{2\pi}{3}\right) \end{bmatrix} + I_0 \begin{bmatrix} \sin(\omega t + \theta_0) \\ \sin(\omega t + \theta_0) \\ \sin(\omega t + \theta_0) \end{bmatrix} \tag{16}$$

At this time, P_{sa}, P_{sb}, and P_{sc} is the three-phase active powers. The MMC-PR three-phase grid-connected active power P_{sj} can be expressed as:

$$\begin{bmatrix} P_{sa} \\ P_{sb} \\ P_{sc} \end{bmatrix} = \frac{1}{2} U_s I_s \begin{bmatrix} 0 \\ \dfrac{\sqrt{3}}{2} \sin\left(\omega t - \dfrac{5\pi}{6}\right) \\ \dfrac{\sqrt{3}}{2} \sin\left(\omega t + \dfrac{5\pi}{6}\right) \end{bmatrix} \begin{bmatrix} \sin\left(\omega t + \theta_i^{+}\right) \\ \sin\left(\omega t + \theta_i^{+} - \dfrac{2\pi}{3}\right) \\ \sin\left(\omega t + \theta_i^{+} + \dfrac{2\pi}{3}\right) \end{bmatrix} \tag{17}$$

$$+ \frac{1}{2} U_s I_0 \begin{bmatrix} 0 \\ \dfrac{\sqrt{3}}{2} \sin\left(\omega t - \dfrac{5\pi}{6}\right) \\ \dfrac{\sqrt{3}}{2} \sin\left(\omega t + \dfrac{5\pi}{6}\right) \end{bmatrix} \begin{bmatrix} \sin(\omega t + \theta_0) \\ \sin(\omega t + \theta_0) \\ \sin(\omega t + \theta_0) \end{bmatrix}$$

Ignoring the system loss, according to the conservation of DC power in each phase of MMC-PR, the DC circulating current of the bridge arm can be defined as I_{dcj} (*j* represents *a, b, c*), which should satisfy

$$I_{dcj} = \frac{P_{sj}}{U_{dc}} \tag{18}$$

Based on the analysis above, it can be seen that the zero-sequence voltage component causes part of the active power to be unevenly distributed among the three phases of MMC-PR, thereby causing differences in the DC circulating current of the bridge arms. Although the arc suppression affects the circulation distribution, it does not impact the operation of the equipment or damage the components.

5. Results

5.1. Parameters

The typical distribution network model with PR shown in Figs. 1 and 2 is built in the software simulation environment, and a variety of SPG fault conditions are simulated to verify the effectiveness and reliability of the proposed flexible voltage arc suppression method. The built model includes three feeders and one MMC-PR with a midpoint grounded between the poles of the high-voltage DC side; the simulation model parameters are shown in Table 1. Among them, the ground damping rate of the distribution network changes with the change of the operation state and structure of the distribution network.

The system-to-ground damping ratio *d* of the distribution network, which is the ratio of the active current component in the residual current to the capacitive current, is equal to the ratio of the ground leakage current to the capacitive current in the neutral point ungrounded system. If the network structure changes, such as a feeder outage maintenance, the network-to-ground damping rate will also change, and the flexible voltage arc suppression of the distribution network grounding fault also needs to consider the change in the damping rate. The flexible arc suppression method based on the improved V_{dc}Q control proposed in this article has good adaptability to the changes in the damping rate.

5.2. Results and analysis

In the case of a neutral point ungrounded distribution network, using the built simulation model, considering the change of the damping rate, the C-phase SPG fault with different fault resistances is set at each fault point, and the proposed method will be verified through simulation.

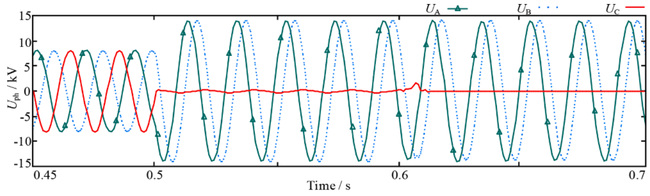
Table 1

Simulation model parameters of typical distribution network with PR.

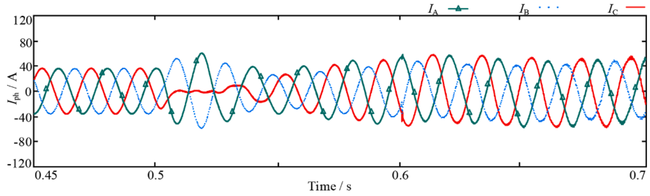
Parameters	Values
System rated voltage U_{N}	10 kV
Number of feeders: *n*	3
Ground conductance of three-phase lines G_{Σ}	3.0×10^{-4} S
Ground capacitance of three-phase lines C_{Σ}	31.5 μF
Ground damping rate *d*	3 %, 3.5 %, 4.5 %
Capacity of PR	2.5 MVA
Inductance of bridge arm L_{ac}	50 mH
Grounding capacitance on DC side C_1	1000 μF
Fault resistance R_{f} (Ω)	10, 100, 1000, 2000, 5000
Fault location	F1, F2, F3
Outer loop of V_{dc}	$K_{\mathrm{p}} = 60$, $K_{\mathrm{i}} = 2$
Current loop of V_{dc}	$K_{\mathrm{p}} = 0.145$, $K_{\mathrm{i}} = 6$
Outer loop of *Q*	$K_{\mathrm{p}} = 0.167$, $K_{\mathrm{i}} = 1$
Current loop of *Q*	$K_{\mathrm{p}} = 0.145$, $K_{\mathrm{i}} = 6$
Outer loop of U_0	$K_{\mathrm{p}} = 0.8$, $K_{\mathrm{i}} = 3$, $K_{\mathrm{d}} = 0.02$
Current loop of U_0	$K_{\mathrm{p}} = 0.15$, $K_{\mathrm{i}} = 1.2$, $K_{\mathrm{d}} = 0.01$

When the damping rate is 4.5 %, while only the feeder connected with PR is operating in the built simulation model of the distribution network, if a C-phase SPG fault occurs at F1 from 0.5 s, then the PR is adaptively put into flexible arc suppression control from 0.6 s. The simulation results are shown in Figs. 6–8.

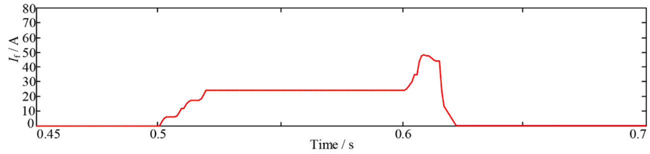
From Fig. 6(a) and Table 2, it can be seen that when a 10 Ω low-resistance SPG fault occurs at 0.5 s, the fault phase voltage U_{C} suddenly changes and rapidly drops to approximately 190 V. And this is the characteristic of SPG fault, the sound phase voltage increases and the fault phase voltage decreases. After the PR is put into the arc suppression control to adjust the fault phase voltage from 0.6 s, the fault phase voltage is reduced to close to 0 V. This is because after the arc suppression control shown in Fig. 4 is put into operation, a zero-sequence voltage quantity is injected into the distribution network, causing the total zero-sequence voltage component in the distribution network to be



(a) Voltage waveforms of three phases

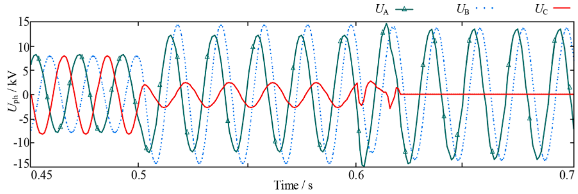


(b) Current waveforms of three phases

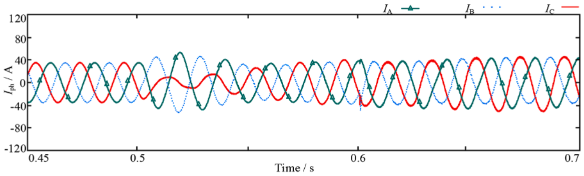


(c) RMS value of fault current

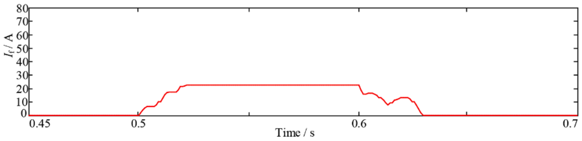
Fig. 6. Waveforms of voltage and current when a fault of 10 Ω occurs at F1 with a damping rate of 4.5 %.



(a) Voltage waveforms of three phases

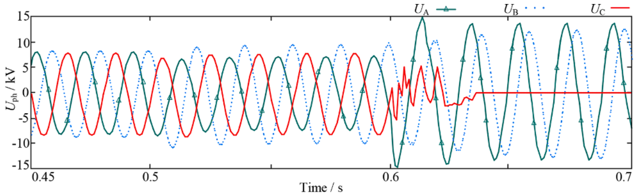


(b) Current waveforms of three phases

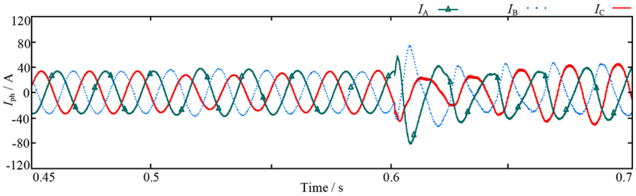


(c) RMS value of fault current

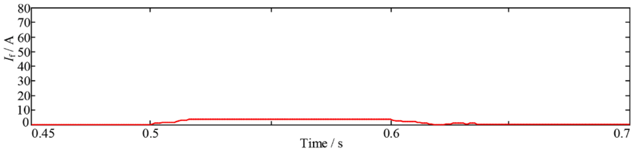
Fig. 7. Waveforms of voltage and current when a fault of 100 Ω occurs at F1 with a damping rate of 4.5 %.



(a) Voltage waveforms of three phases



(b) Current waveforms of three phases



(c) RMS value of fault current

Fig. 8. Waveforms of voltage and current when a fault of 2000 Ω occurs at F1 with a damping rate of 4.5 %.

Table 2

Voltage and circuit RMS values at different fault resistances before and after the F1 fault with a damping rate of 4.5 %.

Damping ratio & fault point	Fault resistance / Ω	Fault voltage / kV		Residual current / A	
		Before input	After input	Before input	After input
4.5 % F1	10	0.19	0.01	19.02	0.90
	100	1.79	0.01	17.92	0.15
	1000	5.47	0.01	5.49	0.01
	2000	5.68	0.01	2.86	0.00
	5000	5.76	0.01	0.84	0.00

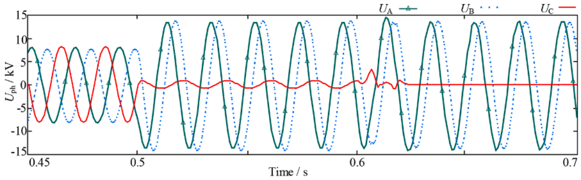
opposite to the electromotive force of the fault phase power source, that is, to make the fault phase voltage close to 0. From Fig. 6(b), after the fault, the fault phase current gradually recovers after a brief fluctuation, and after the arc suppression control is put into operation, the symmetry of the current can also gradually recover. Since the phase currents are greatly influenced by many other factors such as load types, and they have no direct relationship with the arc suppression, this article will not provide further analysis, and will only serve as graphical presentations, as auxiliary explanations to illustrate the system can be still operating normally. From Fig. 6(c) the fault current is also effectively suppressed, and the RMS value of the residual current at the fault point F1 is continuously suppressed to below 1A, then the arc will be extinguished. Also, it can be seen that, there is a short sudden increase of the residual current, this is influenced by the controller's response process. The reason for Fig. 9(c) is the same.

Fig. 6 shows that in the neutral point ungrounded distribution network, PR can independently achieve arc suppression, even without other arc suppression devices.

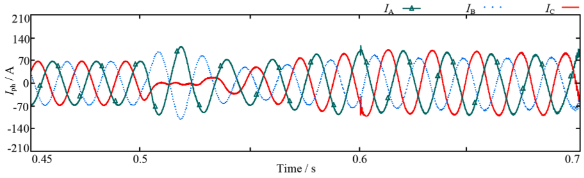
As shown in Figs. 7 and 8, when the fault resistance for grounding faults is 100 Ω and 2000 Ω, respectively, the natural reduced level of fault phase voltage is obviously less than the degree of low resistance 10 Ω as shown in Fig. 6, which is consistent with the fault characteristics. And the PR arc suppression control quickly suppresses the fault phase voltage U_C to below the arc reignition voltage from about 0.6 s because of the injection control of zero sequence quantity, then the residual current at the fault point is reduced to less than 1 A, resulting in the effective extinguishing of the SPG fault arc.

Table 2 and Figs. 6–8 indicate the proposed arc suppression method is effective for SPG faults with different transition resistances.

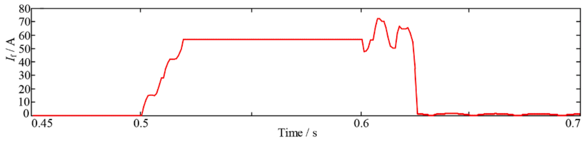
A comparison between Figs. 6–8, together with the Table 2, they reveal that when the fault resistance of the SPG fault is 1000 Ω or even



(a) Voltage waveforms of three phases



(b) Current waveforms of three phases



(c) RMS value of fault current

Fig. 9. Waveforms of voltage and current when a fault of 10 Ω occurs at F1 with a damping rate of 3 %.

5000 Ω, although the voltage drop of the fault phase itself is relatively small after the fault, the PR arc suppression control can still suppress the fault phase voltage U_C to below the arc reignition voltage with good results. Additionally, although the current at the fault point is relatively small because of the larger fault resistance such as 2000 Ω, the proposed arc suppression method can still reduce the residual current at the fault point to below 20 mA. This indicates that, when the fault ground current is small, the proposed controller in Fig. 4 still has good tracking performance, and the PR directly connected voltage arc suppression also has good performance for grounding faults with various fault resistances.

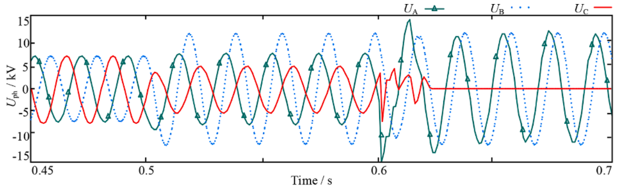
If the damping rate of the distribution network is still 4.5 % when the SPG fault occurs at the bus, a C-phase SPG fault occurs at F2 from 0.5 s, and then PR is put into flexible arc suppression control from 0.6 s. The simulation results are shown in Table 3.

As can be seen from Table 3, after the fault, before the arc suppression control is put into operation, the fault phase voltage U_C at F2 is basically the same as that at F1 under the same damping rate, and the fault current only has a slight difference between 2000 Ω and 5000 Ω. This is because, in this paper, the line impedance is ignored as the analysis of Section 3.1, and only the influence on the ground impedance distribution is considered. After arc suppression control is enabled, the fault phase voltage is suppressed to below the arc reignition voltage under this condition, and the fault residual current is close to zero. The results show that when the fault point is F2 at the bus, the fault voltage and current are basically the same as those at F1. The proposed arc suppression method based on PR control can also effectively suppress the single-phase grounding fault at the bus. It indicates that when the fault point is F2 on the bus, the fault voltage and current are basically the same as point F1. The proposed arc suppression method based on PR control can also effectively suppress the arc in the event of the SPG fault at the bus, that means the method in this paper is adaptable.

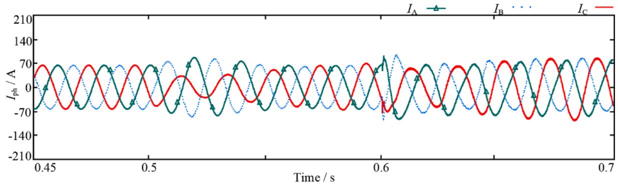
When the damping rate is 3 %, that means all three feeders in the built distribution network simulation model are in operation; If a C-phase SPG fault occurs at F1 from 0.5 s, the PR will automatically input flexible arc suppression control at 0.6 s, the sound phase voltage will increase and the fault phase voltage will finally decrease to near 0 because of the corresponding fault characteristics and zero-sequence injection. It is the same as the other fault conditions. Simulation results are shown in Figs. 9 and 10.

By comparing Fig. 9(c) with Fig. 6(c), it can be seen that the fault residual current increases to 3 times as much as it before, which is caused by the increase of the system capacitance to ground. However, the PR can still effectively compensate the residual current and achieve arc suppression. This is due to, the arc suppression capacity of the traditional dedicated arc suppression device is generally small, and the compensation range is limited. And as a power transmission device that supplies power to loads, the PR can provide a larger capacity for arc suppression and has a larger redundant arc suppression capacity.

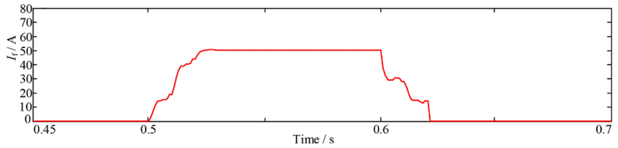
As shown in Fig. 10(a) and (c), when the damping rate is 3 %, the proposed PR arc suppression control can also suppress the fault phase voltage U_C to nearly 0 V, and the residual current at the fault point is almost zero, indicating good arc suppression performance.



(a) Voltage waveforms of three phases



(b) Current waveforms of three phases



(c) RMS value of fault current

Fig. 10. Waveforms of voltage and current when a fault of 100 Ω occurs at F1 with a damping rate of 3 %.

Compared with Figs. 7 and 9, combined with Tables 2 and 4, after analysis, when the damping rate is 3 % and 4.5 %, the fault phase voltage can be reduced to nearly 0 V for fault resistances of 10 Ω, 100 Ω, 1000 Ω, 2000 Ω, and 5000 Ω, and the residual current at the fault point can be suppressed to nearly zero, which can effectively suppress the arc. It indicates that the arc suppression method proposed in this paper will not lose its adaptability to the size of the transition resistance, even if the damping rate changes; and also it will not lose the adaptability to the damping rate, even if the transition resistance changes.

Benefit from the fast tracking response capability of the proposed control method, although the conductance and capacitance of the distribution network to the ground are small, and the damping rate of the system to ground is also slight, the PR arc suppression method can adapt to different damping rates of the distribution network, fast respond to regulate and reduce the fault phase voltage with excellent dynamic performance, demonstrating good arc suppression effectiveness for distribution network with different damping rates.

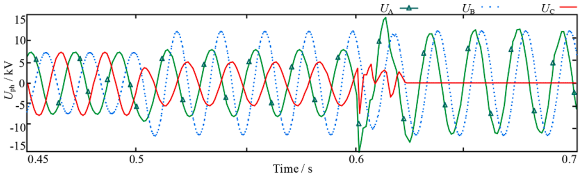
When the damping rate remains at 3 %, change the location of the fault; if the fault occurs at a different feeder other than the one to which the PR is connected, for example, a C-phase SPG fault occurs at F3 from 0.5 s, PR will automatically input flexible arc suppression control at 0.6 s. The simulation results are shown in Fig. 11. From comparing Figs. 10 and 11, as well as Tables 4 and 5, it can be seen that under the same damping rate, the fault phase voltage U_C can be suppressed to below the arcing reignition voltage, and the residual current at the fault point is close to zero, no matter whether the fault occurs on the feeder which PR is connected to or on the other feeders. It indicates that the proposed PR

Table 3
Voltage and circuit RMS values at different fault resistances before and after F2 fault with a damping rate of 4.5 %.

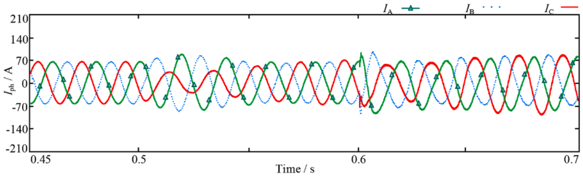
Damping ratio & fault point	Fault resistance / Ω	Fault voltage / kV		Residual current / A	
		Before input	After input	Before input	After input
4.5 % F2	10	0.19	0.01	19.02	1.00
	100	1.79	0.01	17.90	0.14
	1000	5.47	0.01	5.49	0.01
	2000	5.68	0.01	2.87	0.00
	5000	5.75	0.01	1.17	0.00

Table 4
Voltage and circuit RMS values at different fault resistances before and after the F1 fault with a damping rate of 3 %.

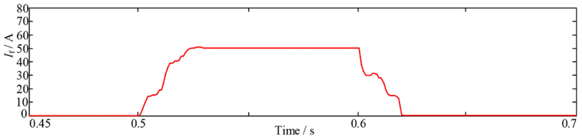
Damping ratio & fault point	Fault resistance / Ω	Fault voltage / kV		Residual current / A	
		Before input	After input	Before input	After input
3 % F1	10	0.57	0.01	56.72	1.35
	100	4.00	0.01	40.01	0.12
	1000	5.72	0.01	5.74	0.01
	2000	5.75	0.01	2.89	0.00
	5000	5.77	0.01	1.17	0.00



(a) Voltage waveforms of three phases



(b) Current waveforms of three phases



(c) RMS value of fault current

Fig. 11. Waveforms of voltage and current when a fault of 100 Ω occurs at F3 with a damping rate of 3 %.

Table 5
Voltage and circuit RMS values at different fault resistances before and after F3 fault with a damping rate of 3 %.

Damping ratio & fault point	Fault resistance / Ω	Fault voltage / kV		Residual current / A	
		Before input	After input	Before input	After input
3 % F3	10	0.57	0.01	56.70	1.29
	100	4.00	0.01	40.00	0.11
	1000	5.72	0.01	5.72	0.01
	2000	5.75	0.01	2.89	0.00
	5000	5.77	0.01	1.17	0.00

high-voltage stage flexible voltage arc suppression method is effective for SPG faults that occur on different feeders.

Combined with Fig. 7(a) and (c), Fig. 11(a) and (c), it illustrates that the proposed arc suppression method has good adaptability to the faults under different damping rates.

The simulation verification mentioned above demonstrates that SPG faults with different fault resistances are simulated in different feeders under different damping rates, and the RMS values of the fault phase voltage and the fault point current before and after the voltage arc suppression based on the PR directly connected are summarized in Tables 2–5. It can be seen that after the proposed arc suppression method is put into operation, the arc suppression method proposed in this article can effectively extinguish the arc for the different fault transition resistances and the variations in damping rate, the fault phase voltage can be effectively reduced to below the arc reignition voltage, and the residual current at the fault point can be suppressed to close to 0 A. This is due to the innovation of the arc suppression principle and the proposed three-phase directly connected zero-sequence voltage injection method, the power capacity advantage of the integrated design of power supply capacity and arc suppression capacity, and the improvement of the proposed control method and controller. It indicates that the proposed method in this article has strong adaptability and good arc suppression effectiveness.

The line voltages of the 10 kV distribution network with PR directly connected are shown in Fig. 12; they include the waveforms before and after the method of flexible voltage arc suppression based on the improved $V_{dc}Q$ control is put into operation. It can be seen that under various operating conditions, the line voltages between the three phases remain symmetrical, and the line voltage waveforms are the same. After the SPG fault occurs at 0.5 s, lasts to the end, although the fault phase voltage U_C drops, the line voltage between the three phases remains symmetrical, and the amplitudes are normal due to the triangular connection mode on the grid side. Starting at 0.6 s, the arc suppression control is put into operation; although the fault phase voltage is further suppressed to below the arc reignition voltage, the line voltages still remain symmetrical, and the magnitudes remain unchanged. Therefore, the flexible voltage arc suppression method by directly connected PR does not change the line voltages of the system and does not affect the normal operation of the distribution network system. The load side of the distribution network transformer remains in normal power supply during the entire fault disposing procedure, safely eliminating the grounding fault and reliably ensuring continuous power supply, safely eliminating the grounding fault and reliably ensuring sustainable power supply.

6. Conclusion

To promote the development of contemporary power systems, this article proposed an innovative flexible voltage arc suppression technique for sophisticated distribution networks with directly connected MMC-PR, based on the high-voltage stage zero-sequence component control of the PR. The proposed method is capable of effectively extinguishing the fault arc under various operating conditions.

1) It adaptively responds to changes in the capacitance current level of the distribution network and variations in the damping rate of the line to earth, avoiding the difficulties of precisely tracking fault currents and measuring ground parameters.
2) The direct source of arc suppression energy is the high-voltage stage DC bus of the PR, which has a large and controllable arc suppression capacity, no additional dedicated arc suppression power supply is required.
3) In the proposed technique, the arc suppression process does not affect the positive and negative sequence controls, nor does it affect the normal operation and power supply of PR ports.

The results demonstrate that the proposed method has good

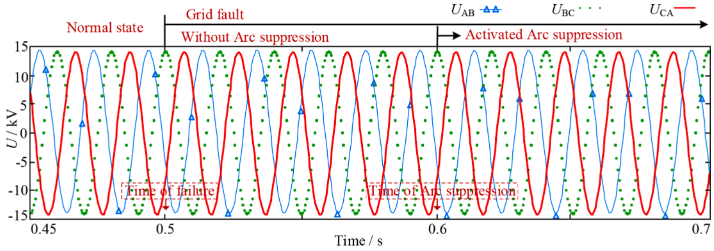


Fig. 12. Waveforms of line voltages between three phases.

operability and adaptability in the arc suppression, which is beneficial to the power supply quality, social public security, and ecological environment protection; the engineering application prospects are broad.

CRediT authorship contribution statement

Lang Jiang: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Xianggen Yin:** Writing – review & editing, Supervision. **Jinmu Lai:** Writing – review & editing, Visualization. **Wei Chen:** Writing – review & editing, Resources, Data curation, Conceptualization. **Minghao Wen:** Resources, Project administration. **Zhenlan Dou:** Funding acquisition. **Jiakun Fang:** Writing – review & editing. **Zilan Xiong:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authers do not have permission to share data.

Acknowledgments

This work was supported by the Science and Technology Project of State Grid Corporation of China under Grant 5400-202199553A-0-5-ZN. The authors are grateful for the financial and technical support of the Science and Technology Project of State Grid Corporation of China.

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