frontiers
in Energy Research

HYPOTHESIS AND THEORY
published: 03 February 2022
doi: 10.3389/fenrg.2022.803142

Distribution Network Voltage Arc Suppression Method Based on Flexible Regulation of Neutral Point Potential of the New Grounding Transformer

***Wu Lifang*[1]*, *Bai Hao*[2], *Zhou Ke*[1], *Yuan Zhiyong*[2], *Yu Xiaoyong*[1], *Lei Jinyong*[2], *Zou Yu*[3] and *Zhang Yuan*[4]**

[1]Electric Power Research Institute of Guangxi Power Grid, Nanning, China, [2]Electric Power Research Institute, China Southern Power Grid, Guangzhou, China, [3]Qinzhou Power Supply Bureau of Guangxi Power Grid Co. Ltd, Qinzhou, China, [4]Chongzuo Power Supply Bureau of Guangxi Power Grid Co. Ltd, Chongzuo, China

Aiming at the problems that the existing arc suppression cabinet technology cannot adjust the zero sequence voltage flexibly and the control and hardware implementation of active arc suppression equipment based on power electronics are difficult, a new method of voltage arc suppression in the distribution network based on the flexible regulation of the neutral point potential of the new grounding transformer is proposed. From the perspective of the sequence component, the variation law of the neutral point voltage before and after the closing of the tapped grounding branch of the new grounding transformer is analyzed. By selecting the appropriate initial tap position of the tap-to-ground switch, the fault phase voltage is flexibly controlled so that the fault phase voltage is reduced to below the reignition voltage to quickly solve the influence of the single-phase grounding fault, and the risk of non-fault phase insulation breakdown is reduced to ensure the stable operation of the distribution network. According to the ratio of the fault phase current to the zero sequence voltage before and after the gear inputs, whether the arc suppression of the single-phase grounding fault is completed is judged. Compared with power electronic products, the new grounding transformer has the advantages of high reliability, long service life, and low cost and has strong economy and applicability in engineering. The single-phase grounding fault model of the 10kV distribution network is built in the PSCAD/EMTDC simulation environment, and the new method of the distribution network voltage arc suppression based on the flexible regulation of neutral point potential of the new grounding transformer is verified. The simulation results show that the proposed method can effectively reduce the fault phase voltage to achieve the reliable arc suppression of the single-phase grounding fault.

Keywords: distribution networks, single-phase grounding fault, neutral point potential, flexible pressure regulating, the voltage arc suppression

Edited by:
Xiangjun Zeng,
Changsha University of Science and Technology, China

Reviewed by:
Junhua Xu,
Guangxi University, China
Narottam Das,
Central Queensland University, Australia

***Correspondence:**
Wu Lifang
837674977@qq.com

Specialty section:
This article was submitted to Smart Grids, a section of the journal Frontiers in Energy Research

Received: *27 October 2021*
Accepted: *04 January 2022*
Published: *03 February 2022*

Citation:
Lifang W, Hao B, Ke Z, Zhiyong Y, Xiaoyong Y, Jinyong L, Yu Z and Yuan Z (2022) Distribution Network Voltage Arc Suppression Method Based on Flexible Regulation of Neutral Point Potential of the New Grounding Transformer. Front. Energy Res. 10:803142. doi: 10.3389/fenrg.2022.803142

INTRODUCTION

The grounding modes of a neutral point in a power system include direct grounding of the neutral point and non-effective grounding of the neutral point. Among them, neutral non-effective grounding includes non-grounding, arc suppression coil grounding, and high impedance grounding (Li, 2019a). Non-effective grounding method accounts for more than 85% of the voltage levels of 6kV–110 kV in the Chinese power grid (Xue, 2015a). In the long-term power system operation, insulation aging, environmental changes, and other conditions are easy to cause short circuit and other problems. Among them, the proportion of the single-phase short-circuit fault is the largest, accounting for more than 60% of the short-circuit fault types (Choi et al., 2010; Fang, 2017). The single-phase grounding fault is often accompanied by the arc grounding fault (Xiao, 2021), which is harmful to personal and equipment safety for a long time, and the arc grounding fault has complex characteristics such as frequent flameout, small arc current, and strong randomness affected by the environment. Therefore, it is difficult to identify and inhibit the single-phase arc grounding fault, and failing to deal with them in time is easy to cause economic losses and personal safety accidents (Zeng, 2000; Liu, 2016).

The existing arc suppression methods of the distribution network mainly use the neutral point arc suppression coil to compensate the capacitive current of the grounding fault point. According to the compensation object, the arc suppression methods of the distribution network can be divided into the current arc suppression method and voltage arc suppression method, and the current arc suppression law can be subdivided into the passive current arc suppression method and active current arc suppression method. The principle of the passive current arc suppression method is that the neutral point of the power grid and the earth are connected by adjustable inductance. When a grounding fault occurs, the inductive current is output through the adjustable inductance to compensate the capacitive current of the fault point system (Jin, 2010; Elombo et al., 2013; Xue, 2015b; Wang, 2018; Chen, 2020). The principle of active current arc suppression is to measure and calculate the fault current through the transformer and inject a zero sequence current with the same size and opposite direction under the premise of the known fault current so as to realize full current compensation arc suppression (Wang, 2015; Xie, 2015; Guo, 2017; Peng, 2018; Wu, 2018; Xu, 2018; Ze-Yin Zheng, 2020). Based on the principle of the current arc suppression method, the team of Li Jinglu of the Changsha University of Science and Technology developed a set of neutral point dynamic grounding devices to inject the compensation current (Li, 2019b), the team of Guo Moufa of Fuzhou University developed the three-phase cascaded H-bridge current converter to inject the compensation current (You, 2016), and the team of Yang Tingsheng of China Ocean Petroleum International Co., Ltd. developed a power electronic switch turn-regulation arc suppression coil to reduce the fault current (Yang, 2021). For the compensation method of the passive arc coil, some scholars have developed a pre-adjusted arc coil (National Development Reform Commission, 2007), air-gap inductive arc suppression coil, and arc suppression coil composed of three cores and five coils (Cai, 2004; Pang, 2006). However, the essence of the current arc cancellation method needs to obtain the fault current value (Zheng, 2021), while it is difficult to obtain the fault current value accurately in the power system engineering application. At the same time, there are problems; for example, the arc residual current is large (Zhang, 2019), and the arc suppression effect is affected by the control mode and the change of the operation state of the distribution network, so it is not widely promoted.

Aiming at the problems of the current arc suppression methods, voltage arc suppression methods came into being. At present, the voltage arc suppression method mostly used on the market is the fault phase transfer arc suppression technology (Grifflel, 1997; Chen, 2019), and its principle is to set up a grounding branch in the station. When a grounding fault occurs, the short-circuit current of the grounding branch is transferred by short-circuiting the fault phase bus in the station, thereby reducing the fault phase voltage to zero. On the basis of the fault phase transfer technology, the State Grid Corporation puts forward the active intervention arc suppression technology (Wang, 2020). The fault phase transfer technology can alleviate insulation deterioration, improve the accuracy of fault location, and it is simple and easy to operate when operating overvoltage occurs. But when metal grounding fault occurs, the grounding fault current is large (Fan, 2019), and there is a risk of the interphase fault under the condition of phase selection failure (Hänninen and Lehtonen, 1998; Xiang, 2020), so its arc suppression effect will be affected (Yao, 2009).

In view of the above problems, based on the principle of suppressing fault phase voltage re-ignition, a voltage arc suppression method for the distribution network based on flexible regulation of the neutral point potential of the new grounding transformer is proposed. The initial gear size is determined by the ceiling function, and then, the initial gear of the primary side of the new grounding transformer is closed; the tapped grounding branch is divided so that the zero potential is offset, and the zero sequence voltage is adjusted. Then, the ratio of the fault phase current to the zero sequence voltage is used to determine whether the arc suppression is completed so as to achieve rapid and flexible regulation of the fault phase voltage and reliable arc suppression. Furthermore, the single-phase grounding fault model of the 10kV distribution network is built in the PSCAD/EMTDC simulation environment to verify the reliability of the new voltage arc suppression method of the distribution network with a flexible voltage control.

THE PRINCIPLE OF NEUTRAL POINT POTENTIAL CONTROLLING STEP-DOWN ARC SUPPRESSION FLEXIBLY

System Equivalent Circuit After Closed Tap Grounding Branch

According to the extinguishing mechanism of the grounding arc, the resistance of a grounding medium is inversely proportional to the fault phase voltage (Huang, 2020), and when the maximum

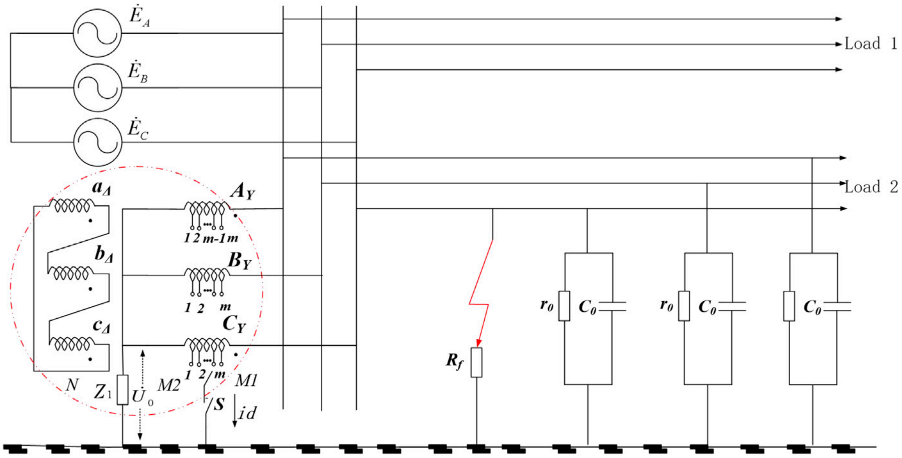


FIGURE 1 | Principle diagram of voltage arc suppression with flexible control of neutral point potential of the grounding transformer.

re-ignition voltage is less than the recovery speed of the grounding medium resistance, the arc is no longer reignited. According to the long-term operation experience of the distribution grid, the critical value of the maximum reignition voltage is between 0.22 and 0.36 times of the phase voltage in the 10kV distribution network (Yao, 2009).

The principle diagram of voltage arc suppression flexibly controlled by neutral point potential of the grounding transformer is shown in **Figure 1**. EA, EB, and EC are electromotive forces of three-phase power supply in the distribution network, $C0$ is the equivalent capacitance of the system to the ground, $r0$ is the equivalent resistance of the system to the ground, and Rf is the grounding fault resistance. AY, BY, and C_Y are the high-voltage side windings of the transformer. Ground taps are set on this side, and m taps are set in total. The taps rise from the neutral point of the high-voltage side transformer to the system in turn, which are 1, 2,. . ., m, respectively. aΔ, bΔ, and cΔ are low-voltage side windings of the transformer, and the neutral point lead of the system is grounded through impedance $Z1$. In addition, $\dot{I}_d$ is the grounding branch current, and the reference direction is the tap flow to the grounding point.

In **Figure 1**, it is defined that the tap-to-system side is defined as the $M1$ side, the tap to the neutral point of the high-voltage side of the transformer side is defined as the$M2$ side, and the transformer low-voltage side is defined as the N side. Then, the original dual-winding transformer can be equivalent to a three-winding transformer.

When a single-phase grounding fault occurs, the grounding branch switches of taps with different tap positions are closed, and the phase and amplitude of the zero-sequence voltage change so that the fault phase voltage changes according to different tap positions. The amplitude of the fault phase voltage is determined by the number of turns of windings contained in different tap positions, and the system line voltage remains unchanged in the process of mobilizing taps with different tap positions.

The transformer is a static component, and its positive and negative sequence impedances are equal, ignoring the line loss. The equivalent circuit diagrams of the positive sequence, negative sequence, and zero sequence of the system are drawn as shown in **Figure 2**. The 1-1′ port corresponds to the grounding transformer and the ground, and the 2-2′ port corresponds to the fault point and the ground.

In **Figure 2**, $X1a$, $X1b$, and$X2$ are the $M1$, $M2$, and N side winding leakage reactance, ZL is the arc suppression coil impedance value, Zs is the power supply impedance, and Xc is the line to the ground positive sequence or negative sequence reactance. The power supply impedance is far less than the line to the ground positive and negative sequence reactance. In addition, $Xc(0)$ is the line to the ground zero sequence reactance. $\dot{U}1(1)$, $\dot{U}1(2)$, and $\dot{U}1(0)$ are the voltages of the 1-1′ terminal, and $\dot{I}1(1)$, $\dot{I}1(2)$, and $\dot{I}1(0)$ are the currents of the 1-1′ terminal.

For the positive order circuit in **Figure 2A**, it can be described as

$$\begin{bmatrix} \dot{U}_{1(1)} \\ \dot{U}_{2(1)} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} \dot{I}_{1(1)} \\ \dot{I}_{2(1)} \end{bmatrix} + \begin{bmatrix} \dot{U}_{Z1} \\ \dot{U}_{Z2} \end{bmatrix}, \tag{1}$$

For the negative order circuit in **Figure 2B**, it can be described as

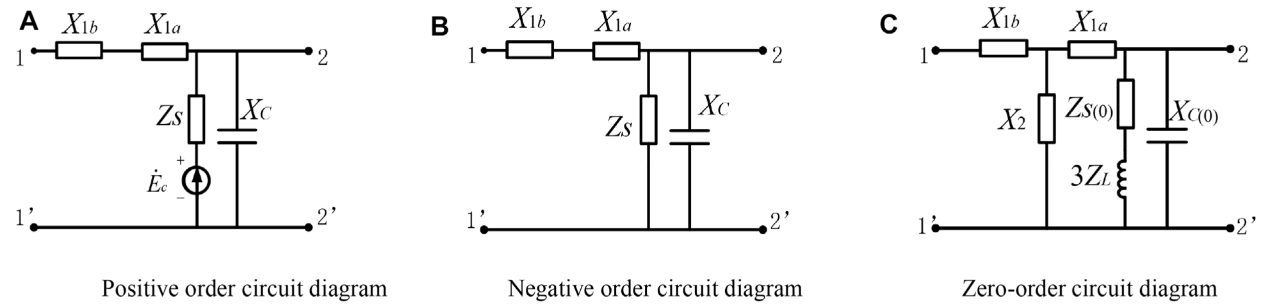
$$\begin{bmatrix} \dot{U}_{1(2)} \\ \dot{U}_{2(2)} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} \dot{I}_{1(2)} \\ \dot{I}_{2(2)} \end{bmatrix}, \tag{2}$$

For the zero-order circuit in **Figure 2C**, it can be described as

$$\begin{bmatrix} \dot{U}_{1(0)} \\ \dot{U}_{2(0)} \end{bmatrix} = \begin{bmatrix} Z_{11(0)} & Z_{12(0)} \\ Z_{21(0)} & Z_{22(0)} \end{bmatrix} \begin{bmatrix} \dot{I}_{1(0)} \\ \dot{I}_{2(0)} \end{bmatrix}, \tag{3}$$

The relevant parameters are as follows:

$$Z_{11} = X_{1a} + X_{1b} + \frac{jX_C Z_S}{Z_S + jX_C} \approx X_{1a} + X_{1b} + Z_S, \tag{4}$$



Positive order circuit diagram

Negative order circuit diagram

Zero-order circuit diagram

FIGURE 2 | Positive, negative, and zero-sequence equivalent circuit diagrams. **(A)** Positive-order circuit diagram **(B)** Negative-order circuit diagram **(C)** Zero-order circuit diagram

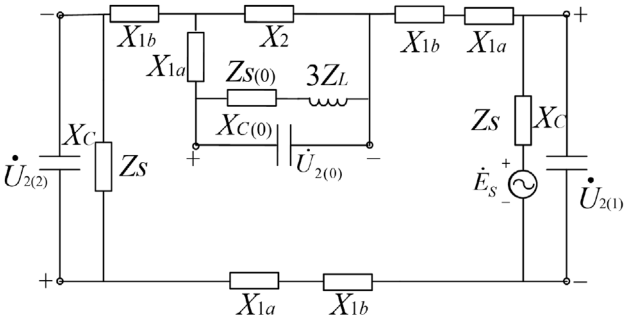


FIGURE 3 | Equivalent sequence diagram of the system.

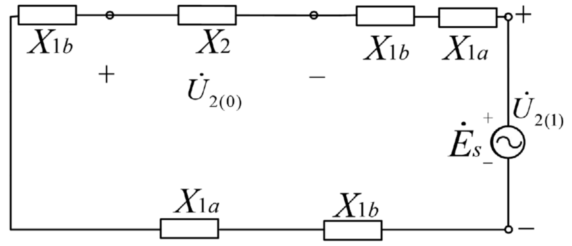


FIGURE 4 | Simplified equivalent sequence diagram.

$$Z_{12} = Z_{21} = Z_{22} = \frac{jX_C Z_S}{Z_S + jX_C} \approx Z_S, \tag{5}$$

$$\dot{U}_{Z1} = \dot{U}_{Z2} \approx \dot{E}_c. \tag{6}$$

As $Z_{S(0)}$ is far less than $3Z_L$ in **Figure 2C**, $Z_{S(0)}$ can be ignored, and then, the relevant parameters in **Eq. 3** are

$$Z_{11(0)} = X_{1b} + \frac{X_2\left[X_{1a}\left(3Z_L + jX_{C(0)}\right) + 3Z_L jX_{C(0)}\right]}{\left(X_2 + X_{1a}\right)\left(3Z_L + jX_{C(0)}\right) + 3Z_L jX_{C(0)}}, \tag{7}$$

$$Z_{12(0)} = Z_{21(0)} = \frac{Z_L X_2 X_{C(0)}}{X_{C(0)}\left(X_2 + X_{1a}\right) - j3Z_L\left(X_2 + jX_{C(0)} + X_{1a}\right)}, \tag{8}$$

$$Z_{22(0)} = \frac{X_2\left[X_{1a}\left(3Z_L + jX_{C(0)}\right) + 3Z_L jX_{C(0)}\right]}{\left(X_2 + X_{1a}\right)\left(3Z_L + jX_{C(0)}\right) + 3Z_L jX_{C(0)}}, \tag{9}$$

When the transformer tap is grounded, there are

$$\dot{U}_{1(1)} + \dot{U}_{1(2)} + \dot{U}_{1(0)} = 0, \tag{10}$$

$$\dot{I}_{1(1)} = \dot{I}_{1(2)} = \dot{I}_{1(0)}, \tag{11}$$

According to the positive, negative and zero-sequence equivalent circuit diagrams in **Figure 2** and **Eqs 10, 11**, the equivalent sequence network of the system is obtained, as shown in **Figure 3**.

In the positive and negative sequence circuit diagrams, the capacitive reactance Xc is greatly large and the internal resistance Zs is greatly small, which can be approximately ignored; when there is no arc suppression coil in the zero-sequence circuit diagram, the capacitance reactance of zero-sequence capacitance to ground is greatly large, which can be approximately ignored. If there is an arc suppression coil, since the detuning of the system generally does not exceed ±15%, the admittance value after parallel connection is relatively small, and the current value flowing over $X1a$ is greatly small. At this time, the branch in series with $X1a$ after parallel connection of the arc suppression coil and ground capacitance can be regarded as an open circuit, and $\dot{U}2(0)$ can be approximately regarded as the voltage at both ends of $X2$. Therefore, the equivalent sequence network diagram of the system in **Figure 3** can be simplified to obtain the simplified equivalent sequence network diagram of the system, as shown in **Figure 4**.

Zero-Sequence Voltage Phase After Closed Tap Grounding Branch

It can be seen from **Figure 4** that $\dot{U}2(1) = \dot{E}s$. It can be seen from **Eq. 2** that $\dot{U}2(2) = Z21\dot{I}1(2) + Z22\dot{I}2(2)$. It can be seen from **Eq. 5** that $Z21 = Z22 = Zs$, and internal resistance Zs is extremely small, so $\dot{U}2(2) \approx 0$, that is, the negative sequence voltage at the fault point is very small, so the fault phase voltage is the sum of the positive sequence voltage and zero sequence voltage, namely, $\dot{U}f = \dot{E}s + \dot{U}2(0) = \dot{E}s + X2\dot{I}1(0)$. Assuming that the phase of $\dot{E}s$ is θ since all components in the series circuit in **Figure 4** are

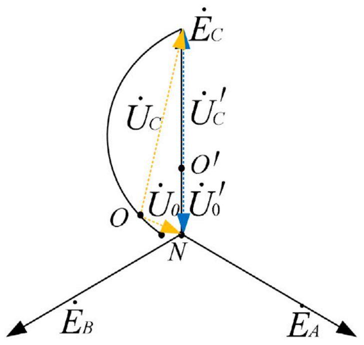


FIGURE 5 | Diagram of the system voltage variation before and after closure of the tap earthing branch.

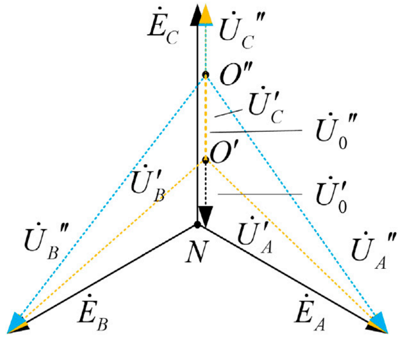


FIGURE 6 | Diagram of the system voltage change with the change of the grounding tap of the transformer.

TABLE 1 | Maximum reignition voltage under different detuning degrees of the distribution network.

Take-off of concordance	Maximum reignition voltage/kV	The peak time/s
–0.1	1.74	0.25
–0.05	1.47	0.43
0	0.86	0.01
0.05	1.52	0.36
0.1	1.83	0.23

inductive, the voltage phase of the two ends of $\dot{U}2(0)$ is $(\theta+180^\circ)$, that is, the zero-sequence voltage phase at the fault point after closing the tapped grounding switch will be approximately opposite to the positive-sequence voltage phase.

Therefore, it is known that after closing the primary side of the new type of the grounding transformer–tapped grounding branch from the perspective of sequence component analysis, the zero potential point offsets making the phase of the zero sequence voltage and phase voltage opposite and reducing the fault phase voltage so as to achieve the arc suppression. The voltage phasors of the system before and after the closing of the tap grounding branch after the single-phase grounding fault occurs are shown in **Figure 5**.

In **Figure 5**, N is the neutral point of the system, O is the zero potential point when the single-phase grounding fault occurs, $\dot{U}0$ is the zero sequence voltage, that is, the neutral point voltage of the system, and the fault phase voltage is $\dot{U}C$. After closing the tap grounding branch to adjust the fault voltage, zero potential will shift to point O', the neutral point voltage of the system is $\dot{U}'0$, and the fault phase voltage will be reduced to $\dot{U}'c$. Furthermore, the phase of $\dot{U}'0$ is opposite to that of $\dot{U}'c$.

Zero-Sequence Voltage Amplitude Under Different Gears

It can be seen from **Figure 4** that the zero-sequence impedance $Z0 = X2$ of the system. According to the transformer short-circuit grounding formula (Jiale, 2010), the expression of $Z0$ is:

$$Z_0 = \omega(1-x)^2 N_1^2 (\frac{S}{\rho L} - \lambda 0), \tag{12}$$

where x is the ratio of turns of the $M2$ side winding to turns of the primary side winding, and its value range is [0,1]. ω is the angular frequency, $\lambda 0$ is the magnetic conductivity of the iron core, S is the cross-sectional area of magnetoresistance, ρ is the magnetic leakage magnetoresistance, and L is the length of the magnetic circuit. As the gear is adjusted, it changes x. Therefore, taking x as the independent variable and deriving $Z0$, we get

$$Z_0' = 2\omega N_1^2 (x-1)\left(\frac{S}{\rho L} - \lambda 0\right), \tag{13}$$

It can be seen from **Eq. 13** that with the increase of x in the value range, the zero-sequence impedance decreases monotonically. With the continuous increase of gear, the system zero-sequence impedance decreases, resulting in the increase of the loop zero-sequence current and system zero-sequence voltage $\dot{U}2(0) = 3\dot{I}0Z1$. Adjust the gear size of the tap grounding branch, and the change of relevant voltage phasors of the system are shown in **Figure 6**.

It can be seen from **Figure 6** that when a fault occurs, the tap grounding branches of different gears are closed, and the zero potential point shifts and moves in the direction of the phase voltage. Therefore, the zero-sequence voltage changes after closing the tap grounding branches of different gears. So with the increase of gears, the zero potential point gradually increases, and the fault phase voltage decreases.

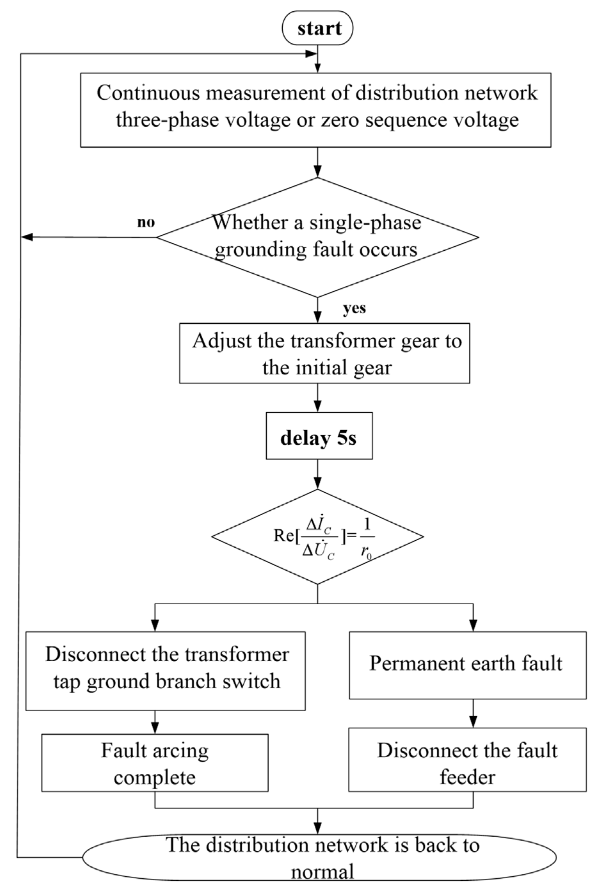


FIGURE 7 | Voltage arc suppression flow chart with flexible voltage control.

INITIAL GEAR SELECTION AND THE ARC SUPPRESSION CRITERION

In order to quickly extinguish the arc in case of a fault, it is necessary to set an appropriate initial gear. Under the initial gear, the critical value of the maximum reburning voltage should be greater than or equal to the fault phase voltage, and the maximum reburning voltage $Ucrm$is made, that is, $Ucrm \geq Uf$. According to the practical application of the project, in the 10kV distribution network, the maximum reignition voltage is different under different detuning conditions. Therefore, after selecting the initial gear, the arc extinguishing effect will be significantly affected under different detuning degrees. The detuning and maximum reburning voltage are shown in **Table.1**.

It can be seen from **Table 1** that the maximum reignition voltage varies with different detuning degrees. Therefore, in order to determine the initial tap position, $Ucrm = Uf = 0.3\dot{E}x$is considered, and $\dot{E}x$ is taken as the x-phase fault phase voltage. When the initial tap grounding switch is closed, the zero-sequence voltage $\dot{U}2(0)$ can be obtained from the equivalent sequence network diagram in **Figure 4**:

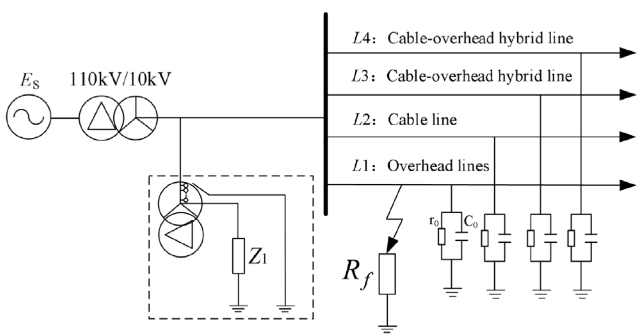


FIGURE 8 | Simulation model of voltage arc extinction with flexible voltage control.

$$\dot{U}_f = \dot{U}crm = \dot{E}c - \dot{U}_{2(0)}, \tag{14}$$

Make the initial gear n; n shall meet

$$\frac{\dot{E}c - \dot{U}crm}{\dot{E}c} = \frac{n \times \frac{N}{m}}{N}, \tag{15}$$

Furthermore, n obtained from **Eqs 14, 15**

$$n = 0.7m, \tag{16}$$

This is because the maximum reburning voltage is different under different detuning degrees. For example, when the detuning degree is 0.1, it can be seen from **Table 1** that the maximum reburning voltage is about 0.32 times the fault phase voltage. At this time, after the initial gear is determined according to **Eq. 16** for arc suppression, there is still weak arc light leading to reignition, so the initial gear obtained according to **Eq. 16** cannot meet all the actual operating conditions on site. Therefore, in order to ensure that arc suppression can be effectively carried out under different operating conditions and the gear adjustment is step-by-step adjustment, round it up by one time along the absolute value through the ceiling function. At this time, the initial gear n is

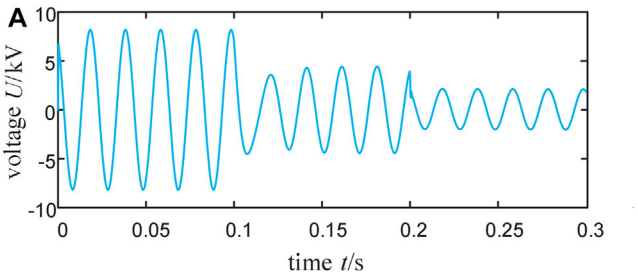
$$CEILING(\frac{\dot{E}x - \dot{U}crm}{\dot{E}x} \times m, 1), \tag{17}$$

After determining the initial gear, in order to improve the safe and stable operation ability, one can be added to the initial gear adjustment to ensure the complete arc suppression. Therefore, it is necessary to determine whether the arc is completely eliminated after adjusting the initial gear, that is, whether the fault phase voltage is zero. If it is not zero, one should be added to the actual initial gear to ensure the complete arc suppression. According to the ratio of the fault phase voltage and the fault phase current before and after the tap connection, the judgment method can determine whether the arc suppression is completed.

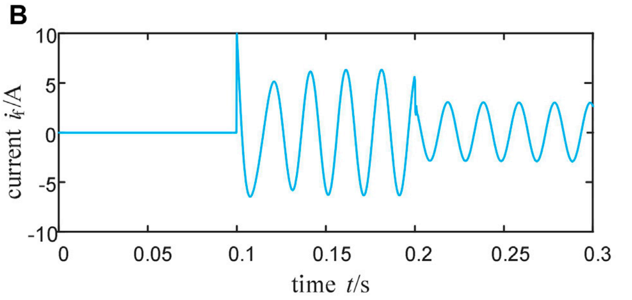
Since the line voltage of the system remains unchanged before and after the fault, ignoring the loss on the line, the current $\dot{I}C$ of the fault phase C before the initial gear is put into operation is

TABLE 2 | Circuit parameters.

The line type	The length of the line/km	The damping ratio/*d* (%)	Ground capacitance/μF	Resistance to ground/kΩ
Overhead line	16	4.00	0.063	1,053
Cable line	16	3.00	0.910	121
Cable-overhead hybrid line	27	3.10	0.875	130
Cable-overhead hybrid line	23	3.21	0.720	163

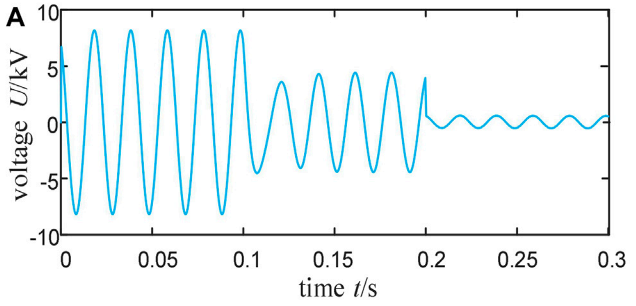


Fault phase voltage waveform

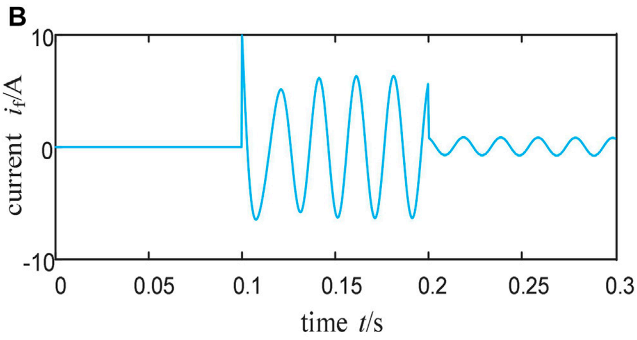


Fault current waveform

FIGURE 9 | Waveforms of the fault voltage and current when tap position is at initial tap position minus 1. **(A)** Fault phase voltage waveform **(B)** Fault current waveform.



Fault phase voltage waveform



Fault current waveform

FIGURE 10 | Waveforms of the fault voltage and current when the tap is at the initial tap. **(A)** Fault phase voltage waveform **(B)** Fault current waveform.

$$\dot{I}c = (\dot{E}c - \dot{U}_0)\left(\frac{1}{R_f} + \frac{1}{r_0} + j\omega C_0\right) + \dot{I}_{TC}, \tag{18}$$

$\dot{I}TC$ is the current of phase C of the grounding transformer. After the initial gear is put into operation, the current $\dot{I}'C$ of the fault phase C is

$$\dot{I}'c = (\dot{E}c - \dot{U}'0)\left(\frac{1}{R_f} + \frac{1}{r_0} + j\omega C_0\right) + \dot{I}Tc, \tag{19}$$

$\dot{U}'0$ is the zero-sequence voltage after the initial gear inputs, and subtract from **Eqs 18, 19** to obtain

$$\Delta\dot{I}C = \Delta\dot{U}_0\left(\frac{1}{R_f} + \frac{1}{r_0} + j\omega C_0\right), \tag{20}$$

where $\Delta\dot{I}C = \dot{I}'C - \dot{I}C$ and $\Delta\dot{U}0 = \dot{U}'0 - \dot{U}0$, and **Eq. 21** can be changed as follows:

$$\mathrm{Re}\left[\frac{\Delta\dot{I}_C}{\Delta\dot{U}_0}\right] = \frac{1}{R_f} + \frac{1}{r_0}. \tag{21}$$

It can be seen from **Eq. 21** that the real part of the fault phase current voltage ratio before and after the initial gear inputs is $\frac{1}{r0}$, and then, the arc suppression is completed. Therefore, when a fault occurs, in order to quickly carry out the arc suppression, turn on the initial gear switch. According to the above analysis, the fault phase voltage is equal to the sum of the positive sequence voltage and zero sequence voltage; the positive sequence voltage is opposite to the zero sequence voltage, and the fault phase voltage is lower than the reburning voltage. The completion of the arc suppression is determined by judging the real value of the ratio of the fault phase current and voltage before and after the initial gear inputs. The new voltage arc suppression method proposed in this study only needs to set tap on the high-voltage side winding of the

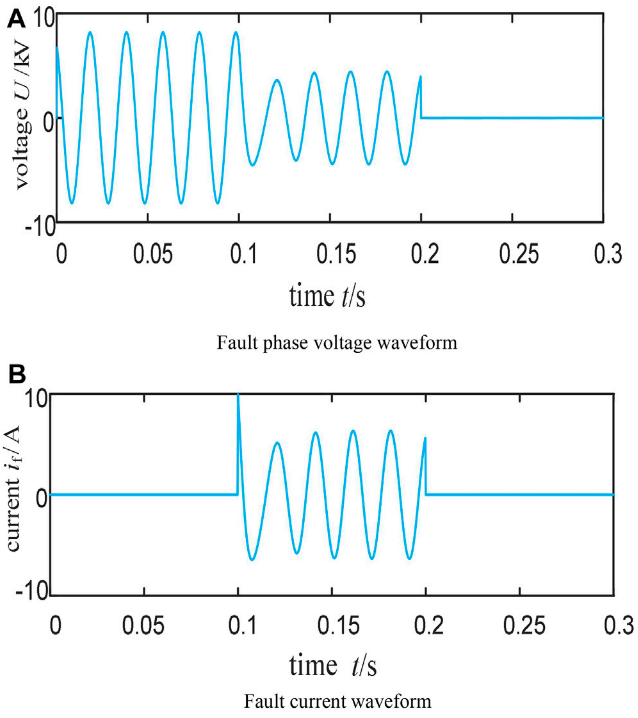


FIGURE 11 | Waveforms of the fault voltage and current when tap position is at initial tap position plus 1. **(A)** Fault phase voltage waveform **(B)** Fault current waveform.

grounding transformer at the head end of the distribution network to realize flexible voltage control, make the fault phase voltage change with the change of the zero-sequence voltage, reduce the fault phase voltage, realize the arc suppression, and solve the single-phase grounding fault with high reliability, fast response, low investment cost, and easy implementation.

REALIZATION PROCESS OF THE VOLTAGE ARC SUPPRESSION

The implementation method of the single-phase grounding fault voltage arc suppression in the distribution network is shown in **Figure 7**. The three-phase voltage or the zero sequence voltage of the distribution network is measured in real time through the measuring elements. When the measurement results show that the 3% phase voltage is less than the change of the zero-sequence voltage or 15% phase voltage is less than the zero-sequence voltage, it is considered that a single-phase grounding fault has occurred in the distribution network. Adjust the gear of the grounding transformer to the initial gear. Then, after a delay of 5 s, judge whether the real part value of the fault phase current voltage ratio before and after the initial gear inputs is equal to $\frac{1}{r0}$. If it is not equal, it is judged as a permanent grounding fault and disconnect the fault feeder. And, if it is equal, disconnect the grounding branch switch of the transformer gear so that the fault arc suppression completes and the normal operation of the distribution network restores.

In the early design scheme of the distribution network, the requirements for transformer capacity are high, resulting in high energy consumption and high actual power cost. At present, the distribution network has innovated the transformer. For the 10 kV distribution network, a section of bus is generally equipped with 12 lines. Using typical distribution network parameters, the system capacitance current is about 100 A, and the transformer capacity Sb is

$$Sb \approx UIc = \frac{10.5}{\sqrt{3}} \times 100 = 606.2\text{kVA}, \tag{22}$$

Therefore, using a voltage source with small capacity to make the transformer capacity slightly larger than the load can not only reduce loss and improve power efficiency but also realize the flexible control of the zero-sequence voltage.

SIMULATION ANALYSIS

In order to verify the effectiveness of the proposed new voltage arc suppression method based on the flexible voltage control of the grounding transformer, a single-phase grounding fault simulation model of the 10 kV distribution network is built in PSCAD/EMTDC software, as shown in **Figure 8**.

Taps at different positions are set at the primary winding side of the transformer. Build various line hybrid models in the PSCAD/EMTDC simulation environment, including the cable line, overhead line, and cable and overhead line hybrid. Their parameters are shown in **Table 2**.

In the 10 kV distribution network system, the maximum reburning voltage is $Ucrm \approx 0.3 \times Uc \approx 1.75\text{kV}$. At 0.1s, a single-phase grounding fault occurs in phase C, and the grounding resistance is 700Ω. Adjust the gear at 0.2s, and

TABLE 3 | Comparison of the voltage and current of the fault phase before and after the adjustment of the gear position in different gear positions.

Gear	State of the gear	Maximum fault phase voltage/kV	Maximum fault current/A
The initial gear minus 1	Before shifting gear	5.372	6.057
	After shifting gear	2.146	3.066
The initial gear	Before shifting gear	5.119	6.474
	After shifting gear	0.610	0.871
The initial gear plus 1	Before shifting gear	5.020	6.535
	After shifting gear	0	0

simulation analysis is carried out at initial gear minus 1, initial gear and initial gear plus 1, respectively. The waveform diagrams of the fault phase voltage and fault current are obtained, as shown in **Figures 9**, **10**, **11**.

From **Figures 9**, **10**,**11**, it can be seen that the single-phase grounding fault occurs in 0.1 s, and the system is asymmetric, resulting in the zero-sequence voltage and fault current. In 0.2 s, adjust the gear. According to the changes of the fault phase voltage and fault current when adjusting different gears, it can be seen that with the adjustment of the gear, the fault phase voltage and fault current decrease accordingly, and when the gear is adjusted to the initial gear, the fault phase voltage is lower than the maximum reignition voltage, which can effectively prevent arc reignition. Record the fault phase voltage and fault current before and after the switch is closed in different gears in **Table 3**.

It can be seen from **Table 3** that the ratio of the fault phase current to the zero-sequence voltage increases gradually before and after gear adjustment under different gears. When it is below the initial gear, the ratio of the fault phase current to the zero-sequence voltage is about 0.93, and when it is at the initial gear plus 1, the ratio of the fault phase current to the zero-sequence voltage is about 1.3. Therefore, with the gradual increase of the gear, the fault phase voltage becomes smaller and smaller, and the fault arc suppression effect is gradually enhanced. When adjusted to the appropriate gear, the fault phase voltage is less than the arc reburning voltage to prevent fault reburning, fundamentally destroy the reburning conditions, and complete the voltage arc suppression.

CONCLUSION

Aiming at the problem of the single-phase grounding fault, a new method of voltage arc suppression in the distribution network based on the flexible regulation of neutral point potential of the new grounding transformer is proposed in this study. Taps at different positions are set on the winding of the grounding transformer. By turning on and off taps at different gears, the fault phase voltage is flexibly adjusted. A single-phase grounding fault model of the 10kV distribution network is built in the PSCAD/EMTDC simulation environment. In case of the single-phase grounding fault, turn on the tap to check the change of the fault phase voltage, and then, effectively verify the arc suppression principle of the flexible control voltage proposed in this study. Finally, draw conclusions as follows:

1) From the perspective of a sequence component, a new method of voltage arc suppression in the distribution network based on the flexible regulation of neutral point potential of the new grounding transformer is proposed. By adjusting the initial position of the tap, achieve the arc suppression without measuring the ground parameters. Compared with the current distribution network arc suppression cabinet technology and active arc suppression equipment based on power electronics, zero-sequence voltage regulation is more flexible, control and hardware implementation are more simple, and it has stronger economy and applicability in engineering.
2) Through the selection of the initial tap position by the ceiling function, the zero potential point can be offset after the grounding of the tapped position so that the phase of the power supply voltage of the ground phase is opposite to that of the neutral point voltage, which is beneficial to the arc suppression of the fault. Without directly reducing the fault phase voltage to zero, the non-fault phase voltage does not need to rise to the line voltage, which reduces the risk of the non-fault phase voltage insulation breakdown.
3) Selecting the appropriate initial tap position can reduce the fault phase voltage to below the arc reignition voltage in a short time so as to effectively prevent the arc reignition to realize the rapid arc suppression of the single-phase grounding fault voltage in the distribution network. The arc suppression equipment is of great significance in preventing wildfires, protecting personal safety, and so on. The fault treatment method has theoretical and engineering reference values in the field of grounding fault treatment of the distribution network.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

FUNDING

This study was funded by Guangxi Power Grid Technology Project (ZBKJXM20190061).

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Conflict of Interest: ZY was employed by the Qinzhou Power Supply Bureau of Guangxi Power Grid Co. Ltd. ZHY was employed by the Chongzuo Power Supply Bureau of Guangxi Power Grid Co. Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.