

Adaptive Suppression of Ground Faults in Distribution Networks and Its Exit Strategy

Jianzhang You, Moufa Guo, *Member, CSEE, Member, IEEE*, and Zeyin Zheng, *Member, IEEE*

Abstract—Fires and human casualties caused by single phase-to-ground faults in distribution networks are frequent. However, existing ground fault suppression methods are affected by ground fault resistance. Thus, an adaptive suppression method that seamlessly combines principles of current and voltage suppression is proposed, which has good adaptability to different ground fault resistance. Meanwhile, a multi-criteria ground fault suppression exit strategy matched to adaptive suppression method is proposed to avoid damage of device caused by power backflow, which provides the possibility for reliable and fast exit of the fault suppression device. Experimental results demonstrate effectiveness and advantages of the adaptive suppression method and its exit strategy.

Index Terms—Adaptive suppression method, distribution networks, multi-criteria exit strategy, single phase-to-ground faults.

I. INTRODUCTION

THERE are a large number of transient single-phase grounding faults caused by complex factors, such as lightning strikes, short-term contact of branches with wires, insulator fouling and breakdown, and cable insulation deterioration in distribution networks [1], [2]. Non-effective grounding method, especially the resonance grounding method, has the advantage of automatically eliminating the instantaneous single-phase grounding fault [3]. However, with the large increase in nonlinear loads and cable lines, line-to-ground capacitance current increases. In addition, active components of the ground fault current cannot be compensated by traditional arc suppression coils, and system fault suppression capability is reduced [4], [5]. This may make it difficult for the arc at the fault point to extinguish itself, and insulation of the system is seriously threatened by energy of the grounding current and overvoltage generated by intermittent arc grounding, which may lead to the expansion of the fault [6].

To realize full compensation of ground fault current, an active (flexible) fault suppression technology based on an active inverter has been proposed by related scholars [7].

Different from passive fault suppression technology, fault flexible suppression technology belongs to active suppression and needs a target of control [8]. What's more, when there is no fault in distribution networks or the fault has been eliminated, it must be taken out of operation. According to different control objects, existing flexible fault suppression methods include flexible current suppression method and flexible voltage suppression method [9].

Qu *et al.* [10] proposed a master-slave arc suppression coil (ASC), active current of ground fault is compensated by the slave ASC. Jia *et al.* [11] proposed a three-phase five-column ASC, which integrates a grounding transformer and a master-slave ASC into the same three-phase five-column ASC. Thus, it is small in size. Amezua *et al.* [12] proposed a single-phase inverter is connected to the neutral point of distribution networks through a booster transformer as a flexible suppression device, which can avoid resonant over-voltages caused by ASC. Smirnov *et al.* [13], [14] proposed that three-phase converter is used as a fault suppression device, which can combine fault suppression with power transfer. Current suppression method is adopted by the above devices, and fault current can be fully compensated in theory. However, all of them need to measure ground parameters, which are highly dependent on parameter measurement accuracy. Especially, it is more pronounced in high resistance ground faults. In this case, residual voltage at fault point in high resistance ground faults may be large enough to rekindle ground fault arc [15].

Nikander *et al.* [16], [17] proposed neutral-point voltage of the system should be controlled to be the inverse of the power source voltage of the faulty phase. Zhou *et al.* [18] proposed voltage of the fault phase should be suppressed to zero. All of them use voltage suppression method, which do not need to measure ground parameters. However, bus voltage is approximated as fault point voltage, which is affected by voltage drop of line impedance. In particular, fault point current is suppressed inconspicuously and may be increased in the event of low resistance ground fault [19]. In this case, voltage at fault point is low, which may not affect suppression of the ground arc, but if it is a permanent resistance ground fault, long-term large fault point current may pose a threat to human safety [20]. Thus, a current and voltage adaptive suppression method is proposed in this paper, which can automatically adjust the percentage of current and voltage suppression methods under different ground resistance. The proposed method is less affected by parameter measurements, line impedance voltage drops, and ground fault resistance.

The fault flexible suppression device (FFSD) must be exited

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J. Z. You, M. F. Guo (corresponding author, email: gmf@fzu.edu.cn) and Z. Y. Zheng are with the Institute of Distribution Network and Automation, School of Electrical Engineering and Automation, Fuzhou University, Fuzhou 350108, China.

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in time, when the fault has been eliminated or isolated; otherwise, equipment of the healthy phase operates at phase-to-phase voltage for a long time, which may lead to breakdown of weak link of insulation of the healthy phase. Identification of transient and permanent faults is adopted by the existing exit strategy: if it is judged to be a transient fault, the suppression device is exited; otherwise, the suppression device is restored to suppression [21]. It can be seen the most critical technique of exit strategy is identification of transient and permanent ground faults [22]. Variation of systematic grounding admittance during the exit process is used as an identification criterion by existing exit methods [23], [24]. However, variation of systematic grounding admittance increases with increase of ground fault resistance. In order to ensure accuracy of identification, the threshold of variation of the systematic grounding admittance should be large, but it will affect identification speed and may cause power backfilling in the case of a permanent low resistance ground fault, which may damage the suppression device. Therefore, a multi-criteria exit strategy for ground fault suppression with fast speed and high accuracy is proposed in this paper.

The rest of this paper is organized as follows. In Section II, the existing flexible suppression principle and influencing factors of its suppression effect are introduced. Then, the principle and realization of the adaptive suppression method are given. A multi-criteria ground fault suppression exit strategy is proposed in Section III. Simulation and experimental results are given in Sections VI and V verify effectiveness of the proposed method Section VI concludes the paper.

II. PRINCIPLE OF FLEXIBLE SUPPRESSION OF GROUND FAULTS IN DISTRIBUTION NETWORKS

A. Flexible Grounded Distribution Networks

Figure 1 is a structural diagram of distribution networks with a FFSD, where U_N is neutral-point voltage and E_a , E_b , E_c , U_a , U_b and U_c are A, B and C phase supply voltage and bus phase voltage, respectively. Z_Z is line impedance between the bus and fault point, and U_f is fault point voltage. R_f is ground-fault resistance, and I_f is fault point current. r_{Ai} , r_{Bi} , and r_{Ci} are phase-to-ground resistances of A, B, and C phases of feeder i , respectively. C_{Ai} , C_{Bi} , and C_{Ci} are phase-to-ground capacitances of A, B, and C phases of

feeder i , respectively. I_Z is injection current of the FFSD. L is connection inductance. S is a breaker. $P_i + jQ_i$ ($i = 1, \dots, n$) is load of feeder i . I_{ki} ($k = A, B, C; i = 1, \dots, n$) is current to ground of phase k and feeder i . T_{zt} is grounding transformer. The FFSD has a single-phase 12-cascade H-bridge (CHB) topology, and its DC side power supply is provided by a step-down transformer (MT) and an uncontrollable three-phase rectifier bridge. The controller contains a primary controller and 12 power module controllers, where the primary controller calculates target voltage of the inverter and power module controllers drive power electronic switches of power modules to action according to instructions of primary controller.

Injection current of flexible current suppression method can be obtained from Fig. 1 according to Kirchhoff's current law (KCL) [25]:

$$I_Z = -U'_f(1/r_0 + j\omega C_0) \quad (1)$$

where U'_f is ground fault point voltage before single phase-to-ground fault; $C_0 = \sum C_{Ai} + \sum C_{Bi} + \sum C_{Ci}$ ($i = 1 \sim n$); $r_0 = \sum r_{Ai} + \sum r_{Bi} + \sum r_{Ci}$ ($i = 1 \sim n$), ω is angular frequency.

Similarly, according to Kirchhoff's voltage law (KVL), reference of flexible voltage suppression method should be [26]:

$$U_N = -U'_f \quad (2)$$

B. Influencing Factors of the Suppression Effect of Existing Flexible Suppression Methods

Location of ground fault is random and uncertain, so U'_f cannot be directly measured [27]. It is usually replaced by faulty phase supply voltage at the bus, which is symbolized by E_f . Their difference is line impedance drop, which is represented by symbol U_{mf} .

Residual current at the fault point of flexible current suppression method without considering line impedance voltage drop is:

$$I_{f\delta_I} = (U'_f - E_f)(1/r_0 + j\omega C_0) \quad (3)$$

And residual voltage at the fault point is:

$$U_{f\delta_I} = (U'_f - E_f)(1/r_0 + j\omega C_0)R_f \quad (4)$$

For flexible voltage suppression method, residual current at the fault point without considering line impedance voltage drop is:

$$I_{f\delta_U} = (U'_f - E_f)/R_f \quad (5)$$

Obviously, residual voltage at the fault point is:

$$U_{f\delta_U} = U'_f - E_f = U_{mf} \quad (6)$$

1) Influence of Measurement Accuracy of Ground Parameters on Suppression Effect

Residual current of the flexible current suppression method in (3) includes ground parameters, so the effect of flexible current suppression method is affected by measurement accuracy of ground parameters. Similarly, flexible voltage suppression method is not affected by grounding parameter measurement from (5). Current suppression method is affected by ground parameters. However, residual current and voltage at the fault point will still be smaller than of voltage suppression method when ground fault is low resistance.

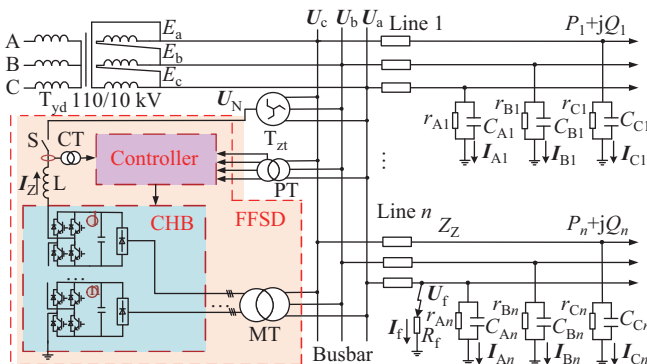


Fig. 1. Distribution networks with an FFSD.

2) Influence of the Line Impedance Voltage Drop on the Suppression Effect

Residual current of flexible current suppression method in (3) includes voltage drop of the line impedance, which means it is affected by line impedance drop. However, voltage drop of line impedance is generally much smaller than power source voltage, so residual current at the fault point is much smaller than fault current. Thus, flexible current suppression method is less affected by voltage drop of line impedance.

Voltage drop of line impedance is also included in (5), so the effect of flexible voltage suppression method is also affected by line impedance voltage drop. When voltage drop of the line impedance is large and the ground fault resistance is small, fault point current may even be increased. This means the flexible voltage suppression method is greatly affected by voltage drop of line impedance during low-resistance ground faults.

3) Influence of Ground Fault Resistance on the Suppression Effect

When flexible current suppression method is adopted, residual current at fault point has no relationship with ground fault resistance in (3), and residual voltage is positively correlated with ground fault resistance from (4). Similarly, ground fault resistance only affects residual current at the fault point of voltage suppression method from (5) and (6). Based on the above analysis, it is easy to obtain when $1/R_f$ is greater than $Y_0 = (1/r_0 + j\omega C_0)$, residual current at fault point of flexible current suppression method is smaller than of flexible voltage suppression method. This means the suppression effect of flexible current suppression method is better than of the flexible voltage suppression method in the case of a low-resistance ground fault. Conversely, effect of flexible voltage suppression method is better when a high-resistance ground fault occurs.

C. Principle and Implementation of Flexible Adaptive Suppression Method

1) Principles of Flexible Adaptive Suppression Method

The relationship between injection current of the FFSD and zero-sequence voltage (neutral voltage) of the system can be obtained as follows from Fig. 1:

$$I_Z = U_0(1/r_0 + j\omega C_0) + (U_0 + E_f)/R_f \quad (7)$$

Assuming $Y_0 = 1/r_0 + j\omega C_0$, (7) can be simplified as:

$$I_Z = U_0(Y_0 + 1/R_f) + E_f/R_f \quad (8)$$

Control objective for adaptive method are both fault point current and fault point voltage. It consists of a current controller and a voltage controller, in which current controller adopts current arc suppression method, and voltage controller adopts voltage arc suppression method.

According to (1) and (2), reference of controllers of the current and voltage suppression methods are, respectively:

$$\begin{cases} I_{Z_ref} = -E_f Y_0 \\ U_{Z_ref} = -E_f \end{cases} \quad (9)$$

In addition, feedback of current controller I_{Z_fb} is shown as (8) and feedback of voltage controller U_{Z_fb} is U_0 . Therefore, deviations of controllers of current and voltage suppression methods can be described by:

$$\begin{cases} \Delta I_Z = I_{Z_ref} - I_{Z_fb} = -(E_f + U_0)(Y_0 + 1/R_f) \\ \Delta U_Z = U_{Z_ref} - U_{Z_fb} = -(E_f + U_0) \end{cases} \quad (10)$$

Assuming both current controller and voltage controller adopt PI control, and PI parameter of current controller is k_{PI} times that of voltage controller. Current and voltage controllers of the adaptive method are operated in parallel, so overall regulation goal of adaptive suppression method is:

$$\begin{aligned} \Delta U_{adp} &= (K_{p1} + K_{i1}/s)\Delta I_Z + (K_{p2} + K_{i2}/s)\Delta U_Z \\ &= (K_{p2} + K_{i2}/s)(k_{PI}\Delta I_Z + \Delta U_Z) \end{aligned} \quad (11)$$

When a high-resistance ground fault occurs, then $|k_{PI}(1/R_f + Y_0)| \ll 1$, that is $|k_{PI}\Delta I_Z| \ll |\Delta U_Z|$ according to (10) and (11); thus, voltage control loop plays a major role, which is:

$$\Delta U_{adp} \approx (K_{p2} + K_{i2}/s)\Delta U_Z \quad (12)$$

Similarly, when a low-resistance ground fault occurs, current control loop plays a major role.

Feedback of current controller I_{Z_fb} and that of voltage controller U_{Z_fb} can be measured by CT and PT. Furthermore, U_f , U_0 , $E_f = U_f - U_0$ and Y_0 can also be measured, so ΔI_Z , ΔU_Z and ΔU_{adp} can be obtained without calculating R_f according to (9)–(11), where information of R_f is contained in I_{Z_fb} and U_{Z_fb} . Meanwhile, current and voltage controllers operate in parallel, that is: ΔI_Z and ΔU_Z have a certain ratio under different ground fault resistances, which can offset errors caused by measurement. Thus, it can be inferred the flexible adaptive suppression method is less affected by ground fault resistance, measurement accuracy of ground parameters and line impedance voltage drop based on previous analysis.

D. Analysis of Control Stability

To analyze stability of the system, a control block diagram of the proposed method is shown in Fig. 2, where

$$\begin{aligned} G_1(s) &= 1/(1/r_0 + sC_0), \quad G_2(s) = 1/(r_L + sL), \\ H_1(s) &= 1/[R_f(1/r_0 + 1/R_f + sC_0)] \\ H_2(s) &= 1/(1/r_0 + 1/R_f + sC_0). \end{aligned}$$

Thus, closed-loop transfer function of the system is:

$$G_i(s) = \frac{\begin{cases} [G_{PI1}(s)R_f + R_f G_1(s)G_{PI2}(s) \\ -G_{PI2}(s)G_1(s)H_2(s)]K_{PWM}G_2(s) \end{cases}}{R_f + [G_{PI1}(s) + H_2(s)G_{PI2}(s)]K_{PWM}G_2(s)R_f} \quad (13)$$

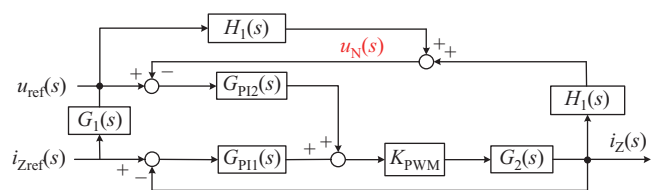


Fig. 2. Control block diagram of the flexible adaptive suppression method.

The method of root locus is used for stability analysis. When $r_0 = 1666 \Omega$, $C_0 = 16.8 \mu\text{F}$, $L = 0.05 \text{ H}$, $K_{p1} = 100$, $K_{i1} = 0.005$, $K_{p2} = 1.1$, $K_{i2} = 0.001$, $R_f = 1 \sim 10 \text{ k}\Omega$, change of system root locus with different grounding resistance is shown in Fig. 3. Characteristic roots of the system are all in the left semi-complex plane, so system is stable. As ground fault resistance decreases, the feature root moves farther away from right half-complex plane, therefore, system becomes more stable.

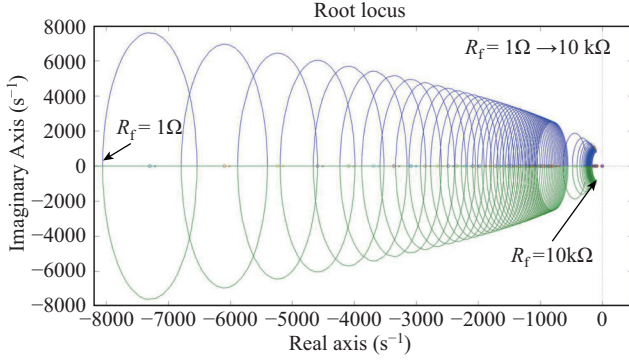


Fig. 3. The root trace of the system with different ground fault resistances.

When $K_{PI}\Delta I_Z = \Delta U_Z$, that is $K_{PI}(Y_0 + 1/R_f) = 1$, output of current and voltage controllers is equal. Based on this, the approximate value of the K_{PI} can be estimated. Then, PI parameters of the controller can be adjusted according to the transfer function and stability analysis.

E. Realization of Flexible Adaptive Suppression Method

When system is normal, ground parameter of the system Y_0 is measured regularly. After a ground fault occurs, ground fault detection is performed [28], which takes duration of the disturbance as one of the criteria. Meanwhile, amplitude and phase of current and voltage are calculated by SOGI and PLL [29]. Then, the proposed adaptive suppression method is used to control fault point current and voltage. Adaptive suppression method adopts current-voltage parallel double closed-loop control, as shown in Fig. 4, which consists of references, feedbacks, deviations, control method, and control objective. First, control references of current controller and voltage controller are $-e_f Y_0$ and $-e_f$ as shown in (9). Second, feedback of current and voltage controller are i_z and u_n , which can be measured directly by CT and PT. Third, deviations are differences between references and feedback as shown in (10). Fourth, control method adopts PI control. Fifth, outputs of current controller and voltage controller are superimposed as overall control objective of the FFSD as shown in (11). Finally, overall control objective is converted into a state signal of each switch through IDCM modulation algorithm [30].

III. EXIT METHOD OF GROUND FAULT SUPPRESSION

A. Traditional Exit Methods for Ground Fault Suppression

The relationship between system neutral-point voltage and injection current of the FFSD is:

$$I_Z = U_N(j\omega C_0 + 1/r_0 + 1/R_f) + E_f/R_f \quad (14)$$

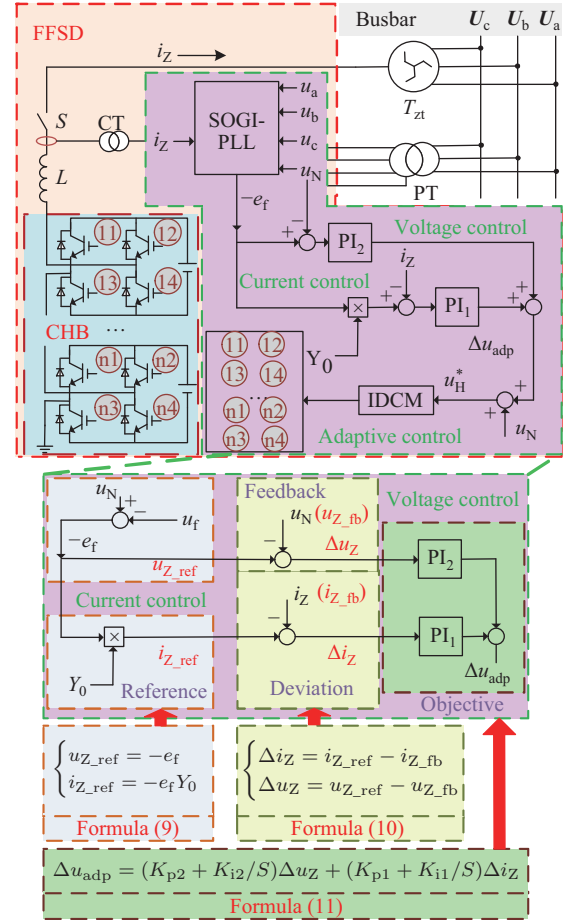


Fig. 4. Simplified diagram of control strategy.

It can be equivalent to:

$$I_Z = kU_N + b \quad (15)$$

After ground fault is eliminated, b in (15) is zero. Therefore, injected current of the FFSD has multiple relationships with neutral-point voltage of the system. According to this feature, it can be identified whether ground fault has been eliminated. However, in the case of a high-resistance ground fault, value of b is very small, and characteristic that ground fault has not been eliminated is very close to characteristic that ground fault has been eliminated. Thus, it is difficult to identify whether ground fault has been eliminated. Therefore, a novel multi-criteria ground fault suppression exit method is proposed as follows.

B. Multi-criteria Identification Method for Exit of Ground Fault Suppression

From (14), equivalent ground admittance of the system is:

$$Y_S = j\omega C_0 + 1/r_0 + 1/R_f + E_f/(U_N R_f) \quad (16)$$

After ground fault is eliminated, system admittance to the ground (Y_S) is $j\omega C_0 + 1/r_0$, which is a fixed value. When ground fault is not eliminated, magnitude of Y_S is related to U_N . As U_N decreases, Y_S increases. Rate of change of Y_S is $k_1 = E_f/R_f$. This means when ground fault resistance (R_f) is larger, Y_S increases more slowly. Therefore, when U_N is

gradually reduced, whether ground fault has been eliminated can be identified by observing change in equivalent ground admittance of system (ΔY_s). But its threshold without power backfill is difficult to select.

Therefore, a new criterion is proposed: grid-connected equivalent diagram of single-phase cascaded H-bridge converter is shown in Fig. 5. According to Kirchhoff's law, grid-connected voltage of converter can be obtained as:

$$L \frac{di_Z}{dt} + R_L i_Z = u_H - u_N \quad (17)$$

where u_H is voltage of CHB, i_Z is current of the FFSD, u_N is voltage of neutral point, R_L and L are inductance and resistance of filter inductor. To inject current into neutral part of system through the FFSD, u_H must be higher than u_N . However, when R_f is small and fault is not eliminated, $u_N \approx -e_f$. If control target value of CHB is reduced, and u_H would be lower than u_N , thus direction of i_Z would be reversed. This means output power of the CHB changes from forward to reverse.

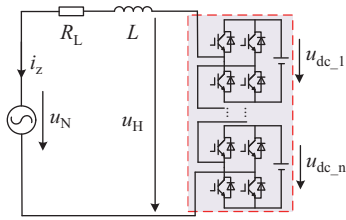


Fig. 5. Equivalent diagram of the CHB grid connection.

Ratio of FFSD injection current to system neutral voltage can be determined from (16). Therefore, power factor angle of I_Z and U_N is:

$$\varphi_N = \arctan\{(\omega C_0)/[1/r_0 + 1/R_f + E_f/(U_N R_f)]\} \quad (18)$$

During arc extinction, $U_N = -E_f$, thus

$$\varphi_N = \arctan(r_0 \omega C_0) \quad (19)$$

At this point, power factor angle is independent of fault resistance. Assuming k is coefficient of reduction and $0 < k < 1$, $U_N = -kE_f$. when FFSD gradually exits and fault has not disappeared, then

$$\varphi_N = \arctan\{(\omega C_0)/[1/r_0 + 1/R_f - 1/(kR_f)]\} \quad (20)$$

Obviously, power factor angle is related to k and R_f . Additionally, the smaller k and R_f are, the faster active power direction becomes reversed.

Based on the above analysis, phase relationship between device injection current and system neutral voltage is shown in Fig. 6, where Fig. (a) and Fig. (b) are 10Ω and 1000Ω resistance ground faults, respectively. U_N^k , I_Z^k , φ_k represent neutral point voltage of the system, the FFSD injection current, and angle between them, respectively, when coefficient of reduction is k .

In Fig. 6, when reference voltage is reduced to $-0.9E_f$, power factor angle exceeds 90° for 10Ω ground fault, which means active power is reversed. In the case of 1000Ω ground fault, active power is reversed when reference voltage drops

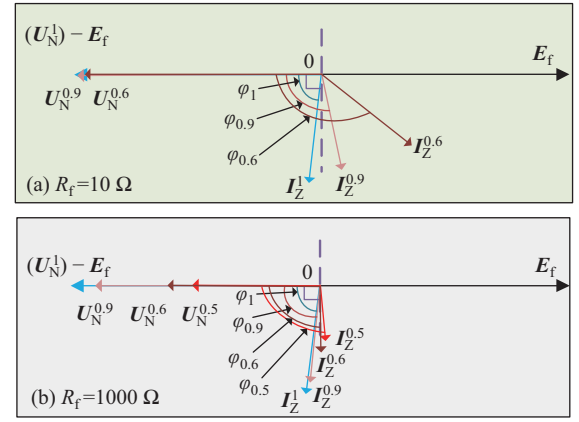


Fig. 6. Phasor diagram of the injection current of FFSD and the voltage at the neutral point of the system.

to $-0.6E_f$. In order to compare proportion of reference values the flexible arc suppression device should reduce when power reverses between different ground fault resistances, suppression state is not immediately restored when active power is reversed. Moreover, for the same ground fault resistance, as reduction increases, power factor angle gradually increases, and eventually exceeds 90° .

Exit process of the FFSD is shown in Fig. 7. When FFSD starts to exit, reference value of current controller is reduced from $I_{Zref} = -E_f(1/r_0 + j\omega C_0)$ to zero in equal proportion according to control cycle. Assume control frequency is f_{sc} , then, value of current reduced each time is $\Delta i_Z = -|I_{Zref}|/f_{sc}$. Similarly, reference value of voltage controller is reduced from $U_N = -E_f$ to zero in equal proportion. At the same time, whether fault has disappeared will be identified. During this period, only amplitude is reduced, and neither phase of the voltage nor phase of current is changed. To prevent power backfilling and improve accuracy when ground fault is not eliminated, ΔY_s and $\cos \varphi_N$ are taken together as a comprehensive criterion. When one meets the threshold, fault is identified as permanent fault. Then the FFSD is restored to the arc suppression state. When u_H drops to a very small value, calculation error of ΔY_s and $\cos \varphi_N$ are very large. Therefore, a threshold value is set for u_N . When u_N is lower than threshold value, it is considered the ground fault has

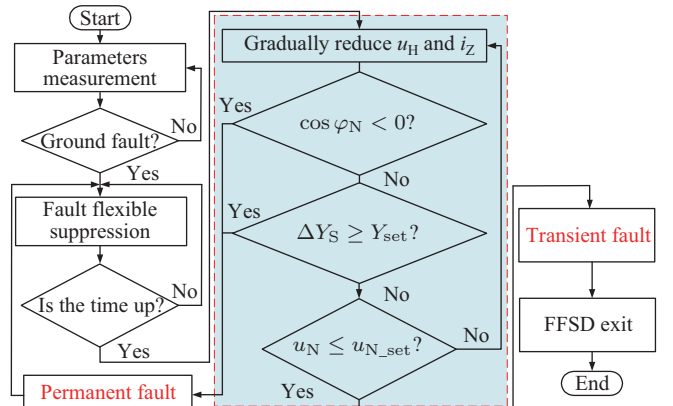


Fig. 7. Flow chart of the exit process of the FFSD.

been eliminated, that is, fault is considered as transient fault. FFSD is directly exited to avoid it refusing to exit. Threshold of u_N is set to 1% of the line-to-ground voltage. Besides, the $\Delta Y_S = Y_S - Y_0 = 1/R_f + \mathbf{E}_f/(U_N R_f)$ according to (16). Assuming current to ground of a 10 kV distribution network is 500 A, and the $Y_0 \approx 0.0866$. In addition, assuming $U_{N_set} = -0.01\mathbf{E}_f$ and upper value of R_f is 10000 Ω , it can be known that $\Delta Y_S \approx 0.1Y_0$. However, it may need to be retuned in other distribution networks.

IV. SIMULATION RESULTS

A. Simulation Model

A simulation model of distribution networks with five feeders was built to verify effectiveness of the proposed adaptive suppression method using PSCAD/EMTDC software. Line types include overhead lines, cabled lines, and combinations of overhead and cabled lines. The Bergeron model is used as simulation model for distribution lines, whose parameters are shown in Table I. Simulation parameters of the primary transformer and distribution transformer are converted from real transformers SZ-31500/110/10.5 and S11-MR-1000/10/0.4, respectively [30]. Parameters of system and FFSD are shown in Table II.

B. Simulation Verification of Influence of Ground Parameter Measurement Accuracy on Suppression Effect

Ground parameter measurement error is set to -10% . The

TABLE I
SIMULATION PARAMETERS OF LINES

Type	Phase sequence	Resistance ($\Omega \cdot \text{km}^{-1}$)	Capacitance ($\mu\text{F} \cdot \text{km}^{-1}$)	Inductance ($\text{mH} \cdot \text{km}^{-1}$)
Overhead line	Zero sequence	0.2750	0.0054	4.6000
	Positive sequence	0.1700	0.0097	1.2100
Cable line	Zero sequence	2.7000	0.2800	1.0190
	Positive sequence	0.2700	0.3390	0.2550

TABLE II
SIMULATION PARAMETERS OF SYSTEM AND FFSD

Parameters	Values
Phase-to-ground resistance r_0 (Ω)	12,796
Phase-to-ground capacitance C_0 (μF)	16.8
System ground current (A)	30
Grounding transformer capacity (kVA)	200
Filter inductor L (mH)	50
Number of H-bridge cascades	12
DC link voltage (V)	800
Current loop proportional ratio K_{p1}	165
Current loop integral ratio K_{i1}	0.01
Voltage loop proportional ratio K_{p2}	3.2
Voltage loop integral ratio K_{i2}	0.005

line at the bus-bar is grounded through a 100 Ω resistance. Fault time is t_1 (0.1 s), and compensation time of voltage type, current type and adaptive type fault suppression devices is t_2 (0.2 s). Residual current at fault point is shown in Fig. 9. Their residual currents are 0.2 A, 2.8 A and 0.5 A. Results show the current suppression method is greatly affected by

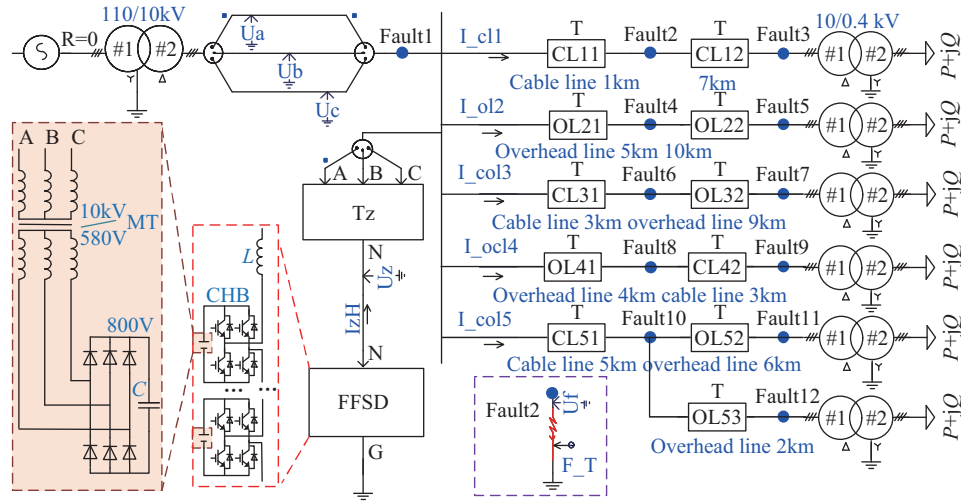


Fig. 8. Topology of simulation model.

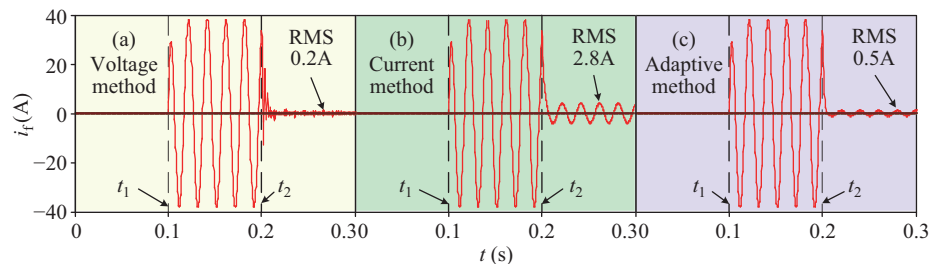


Fig. 9. Residual current at the fault point when different suppression methods are affected by the ground parameter measurement. (a) Voltage method. (b) Current method. (c) Adaptive method.

measurement error of ground parameters, while voltage and adaptive suppression methods are less affected by measurement error of ground parameters.

C. Simulation Verification of Influence of Line Impedance Voltage Drop on Suppression Effect

A 0.1Ω resistance ground fault is set on cable line 8 km away from bus-bar, and load current of fault line is 300 A to simulate the situation of large line impedance voltage drop. The meaning of $t_1 - t_2$ is the same as in Fig. 9. Residual current at the fault point is shown in Fig. 10. Simulation results show that fault point current without compensation is 29 A, and becomes 42 A, 2 A and 3 A after compensation by voltage method, current method and adaptive method, respectively. Fault point current is increased by voltage suppression method, while can still be effectively compensated to a small value by current suppression methods and adaptive suppression methods.

D. Simulation Verification of Influence of the Ground Fault Resistance on Suppression Effect

When resistance of grounding fault is over $1 \text{ k}\Omega$, it is difficult for existing protection devices to guarantee reliable operation [23]. Therefore, critical value of high-resistance and

low-resistance grounding fault is set to $1 \text{ k}\Omega$. Then low-resistance 10Ω and high-resistance $10 \text{ k}\Omega$ ground faults are set on cable line 1 km away from bus-bar. The meaning of $t_1 - t_2$ is the same as in Fig. 9. Residual currents at fault point of voltage-type, current-type and adaptive-type suppression methods are shown in Fig. 11. Results show residual current of flexible current suppression method is smaller than of flexible voltage suppression method when a low-resistance ground fault occurs. When a high resistance ground fault occurs, flexible voltage suppression method has better suppression effect. Flexible adaptive suppression method has good suppression effect on low-resistance and high-resistance ground faults. This is consistent with theoretical analysis results.

E. Simulation Verification of the Exit Strategy

Injection current of suppression device is gradually reduced at t_1 after a 100Ω permanent ground fault is suppressed by FFSD. Variations of $\cos \varphi_N$ and Y_s are shown in Fig. 12, where t_2 and t_3 are their start times, respectively, and ΔY set = $0.02Y_0$. In order to compare changing trends of the criterions, data are normalized. It shows that both of $\cos \varphi_N$ and Y_s can correctly identify the fault has not disappeared. However, the method of Y_s shows power backfill, while $\cos \varphi_N$ can start faster without power backfilling.

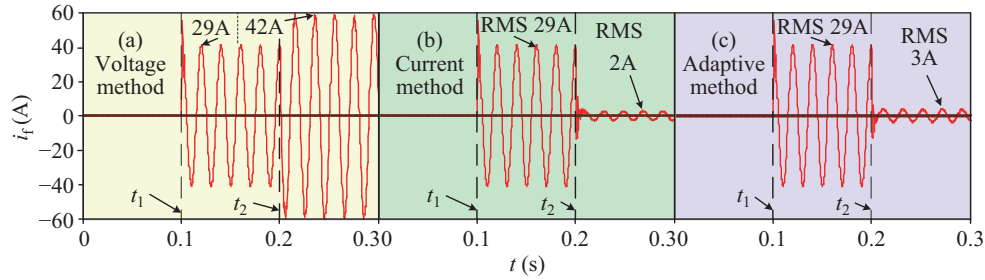


Fig. 10. Residual current at the fault point when different suppression methods are affected by the line impedance drop. (a) Voltage method. (b) Current method. (c) Adaptive method.

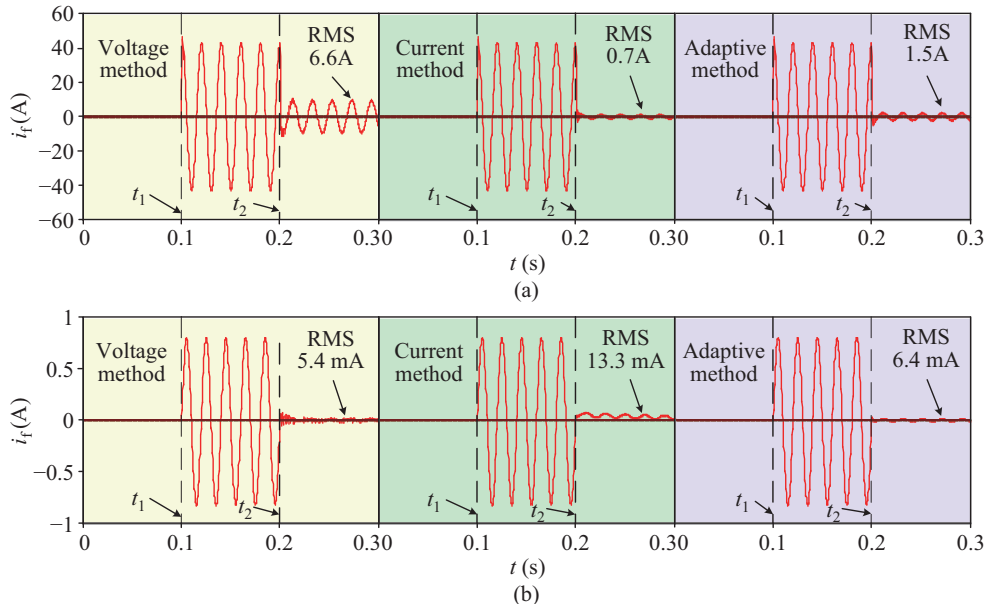


Fig. 11. Residual current at the fault point when different suppression methods are affected by the ground fault resistance. (a) $R_f = 10 \Omega$. (b) $R_f = 10 \text{ k}\Omega$.

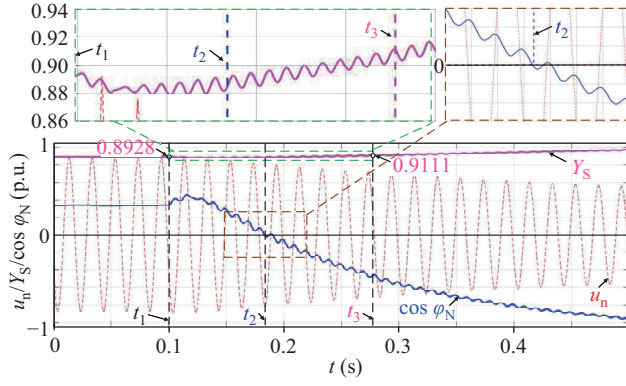
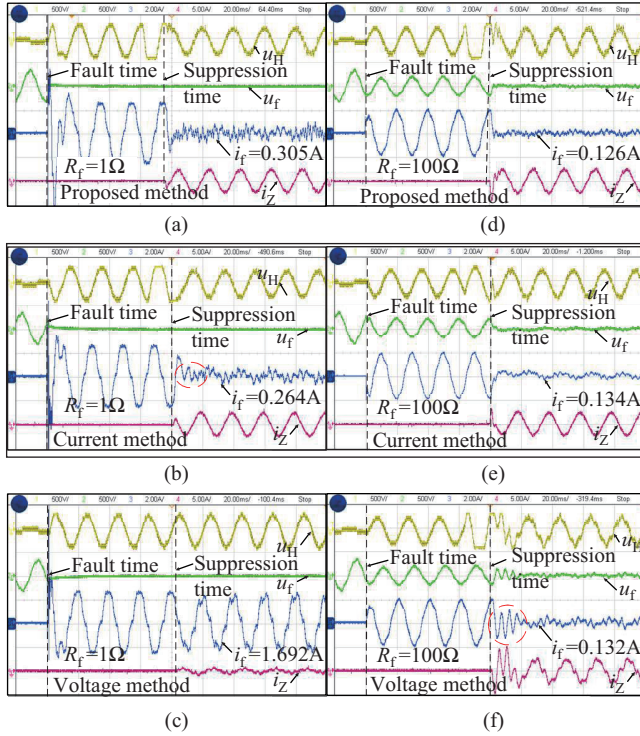


Fig. 12. The variations of criteria when the suppression device exits.

Fig. 13. Experimental waveforms under different suppression methods. (a) $R_f = 1\Omega$ and proposed method. (b) $R_f = 100\Omega$ and proposed method. (c) $R_f = 1\Omega$ and current method. (d) $R_f = 100\Omega$ and current method. (e) $R_f = 1\Omega$ and voltage method. (f) $R_f = 100\Omega$ and voltage method.

V. EXPERIMENTAL RESULTS

A. Physical Simulation Experiments

Experimental system of 0.4 kV described in [29] was used to perform physical simulation experiments. Experimental waveforms of different suppression methods were shown in Fig. 13, where u_H is output voltage of FFSD, u_f is fault point voltage, i_f is fault point current and i_Z is output current of FFSD. Fig. 13(a)~Fig. 13(c) and Fig. 13(d)~Fig. 13(f) are experimental waveforms of 1Ω and 100Ω ground faults, when adaptive suppression method, current suppression method and voltage suppression method are used, respectively. It can be seen residual current at fault point of current suppression method is smallest, followed by adaptive suppression method, and voltage arc suppression method has a weak effect on

current compensation of fault point, in the case of 1Ω resistance ground fault. Fault voltage of current suppression method has an oscillation for about 20 ms at the moment of action, while adaptive suppression method and voltage suppression method have similar response speeds, and there is almost no oscillation. A similar conclusion can be reached at 100Ω resistance ground fault. Therefore, adaptive suppression method has good response speed and accuracy in different ground fault resistances.

Comparison of different fault suppression methods is shown in Table III. It can be seen residual current of current suppression method is large in high-resistance ground faults, and it is greatly affected by measurement accuracy of ground parameters. Voltage suppression method has a large residual current in the event of a low-resistance ground fault, and it is greatly affected by line impedance voltage drop. Adaptive suppression method proposed in this paper can effectively suppress fault point current in both low-resistance grounding faults and high-resistance grounding faults, and it is less affected by measurement accuracy of ground parameters and voltage drop of the line impedance.

TABLE III
COMPARISON OF DIFFERENT SUPPRESSION METHODS

References	Method	Influence		Residual current	
		Y_0	U_{mf}	Low resistance	High resistance
[10]–[15]	current	great	little	small	large
[16]–[18]	voltage	no	great	large	small
	Proposed method	little	little	small	small

B. Industrial Experimental System

An industrial prototype of the FFSD was developed and tested in 10 kV distribution networks to further verify effectiveness of the proposed adaptive suppression method. Distribution networks and device prototype are shown in Fig. 14. Parameters are the same as those in software simulation. DC side power source of the FFSD is independently provided by a step-down transformer. H-bridge (HB) module consists of two parts: rectifier and inverter. The rectifier provides power for DC side of the H-bridge, as shown in Fig. 1.

C. Industrial Experiments of the Flexible Adaptive Suppression Method

The arc ground, 0Ω and $10\text{ k}\Omega$ resistance ground faults are set on L1 of the 10 kV distribution networks in Fig. 14. The suppression effect of the FFSD is shown in Fig. 15, where u_f is fault voltage, u_n is neutral-point voltage, i_f is current of fault point, i_Z is current injected by the FFSD, T1 is ground fault moment, T2 is compensation moment of the FFSD. Experimental results show FFSD can significantly reduce the chance of arc re-ignition and suppress fault point voltage to less than 200 V within 0.5 s under different ground fault resistances, which is within the scope of the standard of residual voltage described in [31] (residual voltage should be suppressed below 250 V in 2 s).

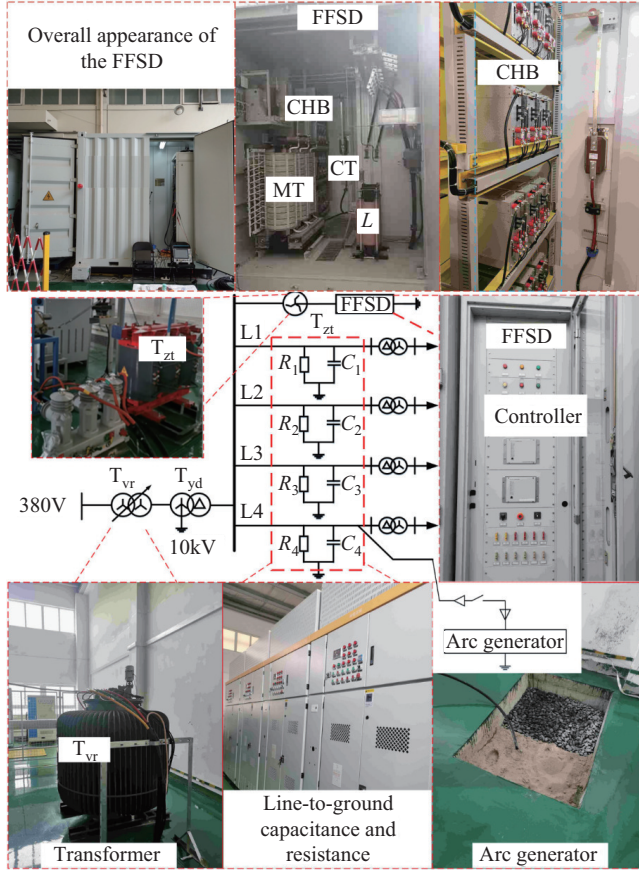


Fig. 14. 10 kV distribution networks and the FFSD prototype.

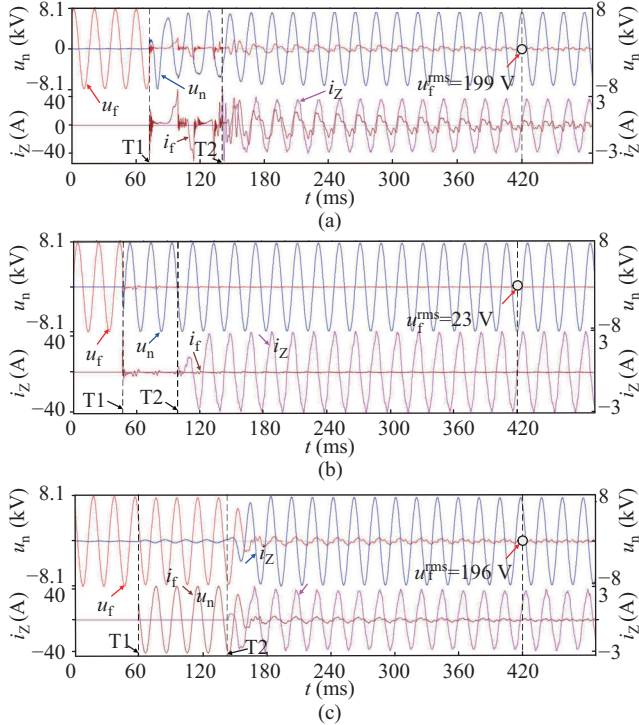


Fig. 15. Compensation effect of the FFSD under arc and different resistance ground faults. (a) Arc ground fault. (b) $R_f = 0 \Omega$. (c) $R_f = 10 \text{ k}\Omega$.

D. Industrial Experiments of the Ground Fault Suppression Exit Method

After a ground fault, FFSD is put into operation for a period of time. Then, current of the FFSD and neutral-point voltage of the system are gradually reduced by controlling the FFSD, and ground fault state is identified, simultaneously. Experimental results when ground fault is not eliminated are shown in Fig. 16, where u_f is fault voltage, Y_S is admittance of the system to the ground, $\cos \varphi_N$ is power factor of the FFSD, T1 is time to start reducing output of the FFSD, and T2 is moment when comprehensive criterion identifies fault that has not disappeared. Experimental results show FFSD would restore fault suppression after ground arc re-ignition. In addition, $\cos \varphi_N$ can identify the fault faster than system admittance to ground in low-impedance ground fault, and slower in the case of a high-impedance ground fault. Therefore, comprehensive criterion is faster and more accurate than single criterion for fault identification.

Comparison of exit methods is shown in Table IV. Existing methods based on ΔY_s cannot determine whether power backfilling is occurring, which may damage DC side of the converter. It can be solved by the proposed method. Meanwhile, multiple criteria can be used as backup for each other, so recognition accuracy of multiple criteria is higher than of single criterion.

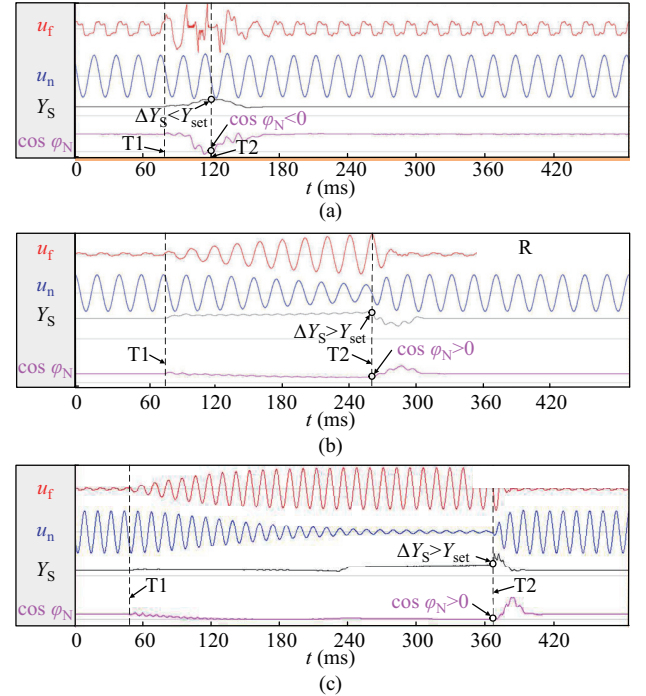


Fig. 16. Exit of the FFSD when the ground fault is not eliminated. (a) Arc ground fault. (b) $R_f = 3 \text{ k}\Omega$. (c) $R_f = 10 \text{ k}\Omega$.

TABLE IV
COMPARISON OF DIFFERENT EXIT METHODS

References	Method	Rapidity	Accuracy	Risk of power backfill
[23], [24]	ΔY_s	medium	good	Yes
Proposed method	$\cos \varphi_N$	good	medium	no
	multi- criteria	good	good	no

VI. CONCLUSION

An adaptive suppression method has been proposed in this paper to solve the problem that existing flexible current suppression methods and flexible voltage suppression methods are greatly affected by measurement accuracy of ground parameters and voltage drop of the line impedance in a neutral-point ungrounded system. At the same time, a novel ground fault suppression exit strategy adapted to the flexible adaptive suppression method is proposed. Ground admittance of system and active power direction of the FFSD are used as identification criteria for ground fault not being eliminated, which improves reliability and rapidity of ground fault suppression exit.

Through software simulation, physical and industrial prototype experimental verification, results show the proposed adaptive suppression method can significantly reduce chance of arc re-ignition under different ground faults. The FFSD using the proposed ground fault suppression exit method can exit correctly.

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Jianzhang You received the M.S. degree in Electrical Engineering and Automation from Fuzhou University, Fuzhou, China, in 2016. He received the Ph.D. degree in Electrical Engineering with Fuzhou University, in 2023. Currently, he is with Xiamen University of Technology.



Zeyin Zheng received the B.S. degree in Electrical Engineering from Fuzhou University, Fuzhou, China, in 2014, and the Ph.D. degree in Electrical Engineering from Yuan Ze University, Taoyuan, Taiwan, China, in 2021. He has been with Fuzhou University, where he is currently an Associate Professor with the College of Electrical Engineering and Automation. His research interests include power distribution systems and automation.



Moufa Guo received the B.S. and M.S. degrees in Electrical Engineering from Fuzhou University, Fuzhou, China, in 1996 and 1999, respectively, and the Ph.D. degree in Electrical Engineering from Yuan Ze University, Taoyuan, Taiwan, China, in 2018. Since 2000, he has been with Fuzhou University, where he is currently a Professor with the College of Electrical Engineering and Automation. His research interests include the information processing, protection control and flexible arc suppression of single-line-to-ground fault in distribution

networks.