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A Hybrid Flexible Neutral Grounding Mode for Large Generators

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Abstract: Single-phase ground faults frequently occur at the generator stator windings. To realize reliable arc suppression, a dual-frequency active arc-suppression strategy has been widely considered. However, the existing method needs an inverter with large capacity, which is large in volume and high in cost, causing limited engineering application prospects. To reduce the capacity, a novel hybrid flexible neutral grounding method for large generators is proposed in this paper. It combines the dual-frequency active arc-suppression strategy with the arc-suppression coil-grounding mode. Thus, most of the fundamental components in the fault current are compensated by the arc-suppression coil, and the rest are compensated by the active arc-suppression device. The capacity of the inverter can be greatly reduced under the premise of reliably realizing arc suppression. To identify transient and permanent ground faults after arc suppression, the phase-angle relation between the third-harmonic voltage and current variation at the generator neutral point is used to form the fault-type identification criterion. The third-harmonic quantities can avoid the blind area at the neutral point caused by fundamental quantities. Simulation and experimental test results verify the effectiveness of the proposed method.

Keywords: arc suppression; hybrid grounding; dual frequency; inverter capacity; fault type

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1. Introduction

Stator winding single-phase ground fault is one of the most common faults of large generators [1]. The large ground fault current produces arc and burns the stator iron core. The lamination of the iron core is sintered together, resulting in maintenance difficulties. Moreover, the ground fault current also destroys the winding insulation and expands the accident. If not effectively suppressed and protected, the single-phase ground fault may develop into a turn-to-turn or phase-to-phase short-circuit fault, which may cause serious damage to the generator [2,3]. In order to reduce the damage and ensure the safe operation of the generator, a reliable ground fault protection method, a suitable neutral grounding mode, effective arc suppression, and an elimination method are the key problems that have attracted a lot of attention by scholars.

At present, the fundamental zero-sequence voltage criterion [4], third-harmonic voltage criterion [5], and low-frequency injection protection criterion [6] are mainly used as the generator stator ground fault protection. The above protection criterion can accurately detect ground faults and isolate the generator from the system to avoid further damage. However, under some cases of minor fault degree, tripping the generator blindly and quickly is not suitable. The sustainable power supply of the system is destroyed, and it is easy to cause large-scale power outage accidents. In addition, for serious ground faults, the residual magnetic field in the stator windings remains for a long time after the generator exciting current drops to zero. Thus, the ground fault current does not disappear and the safety of the stator iron core cannot be guaranteed. Therefore, the fault current should be suppressed to reduce the safety threat.

Generators generally adopt the neutral grounding mode of ungrounded [7], grounding through the arc-suppression coil [8], and grounding through high resistance [9]. For a generator with an ungrounded neutral point, high transient overvoltage is easily caused under single-phase ground faults [10], which destroy the insulation of the stator windings. Thus, it is rarely used in large generators. Compared with the ungrounded mode, the high-resistance grounding mode increases the resistance component in the fault current, which cannot suppress the fault current. The arc-suppression coil-grounding mode can generate inductive current after ground faults and compensate the capacitive components in the fault current [11]. It plays a positive role in restraining the fault current and preventing the fault from spreading. However, it cannot supplement the harmonic components in the fault current, and the residual current can still maintain the arc burning after compensation [12]. Practical operation experience shows that none of the classical grounding mode can achieve reliable arc elimination, and it is still necessary to trip the generator under severe ground faults.

To achieve effective ground fault current suppression and avoid arc ignition, an active arc suppression method is proposed in the literature [13]. By controlling the fault point voltage lower than the arc reignition voltage with an external injected source, the arc suppression can be reliably achieved. Since the phase potential of the generator stator contains a certain amount of third-harmonic potential [14,15], the dual-frequency active arc-suppression algorithm is adopted. However, the method in the literature [13] is applied to a small generator, and the generator neutral point is still grounded through the resistance in the arc-suppression process. As a result, most of the injected power from the active arc-suppression device is consumed by the grounding resistance. Large generators have a high voltage grade and the large capacitive current to ground [16,17]. If the active arc-suppression device is applied in practical engineering, it needs a large-capacity inverter. It is large in volume and costs a lot, which makes it difficult to widely promote.

To reduce the capacity of the inverter, a hybrid flexible neutral grounding method is proposed in this paper, which combines the dual-frequency active arc-suppression device with the arc-suppression coil-grounding mode. The arc-suppression coil can compensate for most of the fundamental components in the ground fault current, whereas the active arc-suppression device only compensates for the third-harmonic components and a small part of the fundamental components. Therefore, the capacity of the inverter can be greatly reduced, and only 20 kVA can meet the requirements of arc extinguishing. After arc suppression, to identify the transient and permanent ground faults, a fault-type identification criterion is proposed based on the phase-angle difference between the third-harmonic voltage and current variation at the generator neutral point. The third-harmonic quantities can avoid the blind area at the neutral point caused by the fundamental quantities. Simulation and dynamic experimental test results show that the proposed method is not affected by the fault scenario, generator operation mode, and generator excitation regulation, which can realize reliable arc suppression and fault-type identification.

2. Hybrid Flexible Neutral Grounding Mode for Large Generators

2.1. Arc Suppression Mechanism

Belikov's theory indicates that when the peak voltage of arc extinguishing is less than the medium recovery strength of the arc channel, the arc will be extinguished. Otherwise, the arc will reignite [18]. To achieve reliable arc suppression and prevent the arc from reignition, the fault-point voltage should be suppressed below the arc-reignition voltage. Since the generator stator windings stay in a closed environment, the fault-point voltage remains relatively stable when the arc burning is caused by ground faults. In this paper, the fault is suppressed in essence, and the suppression goal of the fault point voltage is 0.

Figure 1 shows the generator stator-winding schematic diagram based on the hybrid flexible neutral grounding mode. The symbols used in this paper are listed in Table 1. The phase potential of the generator is mainly composed of fundamental and third-harmonic components [2,13]. Each phasor in Figure 1 contains fundamental and third-harmonic

components, represented by the subscripts "$_1$" and "$_3$," respectively. Since the content of other harmonics is too low to maintain the arc burning, they are not considered in this paper.

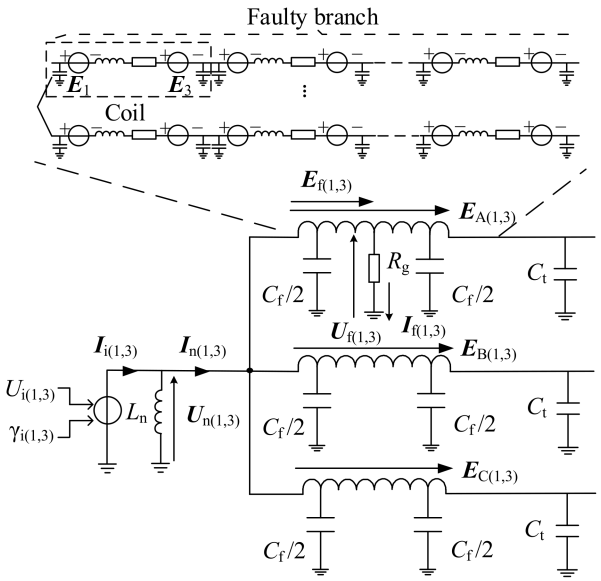


Figure 1. Generator stator-winding schematic diagram based on the hybrid flexible neutral grounding mode.

When a single-phase ground fault occurs, the ground-fault current is mainly composed of capacitive current provided by the grounding capacitor. The arc-suppression coil produces the inductive current, which can compensate for the power frequency capacitive current in the fault current. However, it can only compensate for the fundamental frequency part of the fault current; the rest of the fundamental frequency component and the third-harmonic component are compensated for by the active arc-suppression device.

The dual-frequency active arc-suppression device can force and maintain the voltage at the generator neutral point by arbitrarily regulating the amplitude and phase of the output voltage. According to Kirchhoff's voltage law, the voltage at the fault point satisfies that:

$$\boldsymbol{U}_{f(1,3)} = \boldsymbol{U}_{n(1,3)} + \boldsymbol{E}_{f(1,3)} \tag{1}$$

The online calculation method of the fundamental and third-harmonic fault potential $\boldsymbol{E}_{f(1,3)}$ is given in the literature [13]. When the fault-point voltage is regulated to 0, based on Equation (1), the voltage at the neutral point should meet the following requirements:

$$\boldsymbol{U}_{n(1,3)} = -\boldsymbol{E}_{f(1,3)} \tag{2}$$

When the neutral-point voltage is regulated as $-\boldsymbol{E}_{f(1,3)}$, the fundamental and third-harmonic voltages at the fault point are both suppressed to 0, as shown in Figure 2. Thus, the fundamental and third-harmonic components in the fault current can be effectively suppressed.

Table 1. Nomenclature table.

Symbols	Description
E_A	Electric potential of phase A
E_B	Electric potential of phase B
E_C	Electric potential of phase C
E_1	Fundamental coil potential of the first coil in the faulty branch
E_3	Third-harmonic coil potential of the first coil in the faulty branch
C_f	Equivalent grounding capacitance of the generator stator windings for per phase
C_t	Equivalent grounding capacitance of the directly connected equipment for per phase
R_g	Grounding transition resistance
U_f	Fault point voltage
I_f	Fault current
U_n	Generator neutral-point voltage
I_n	The current flowing through the neutral line
L_n	Equivalent inductance value of the arc-suppression coil
U_i	The amplitude of the output voltage by the active arc-suppression device
γ_i	The phase angle of the output voltage by the active arc-suppression device
I_i	The injected current from the active arc-suppression device
E_f	Fault potential (the induced potential between the generator neutral point and the fault point)
f	The fault point
L_0	Inductance value of the filter in the active arc-suppression device
C_0	Capacitance value of the filter in the active arc-suppression device
C_{dc}	Capacitance value of the DC side in the active arc-suppression device
R_{dc}	Resistance value of the DC side in the active arc-suppression device
ΔU_{n1}	Fundamental neutral-point voltage variation after putting in the active arc-suppression device
ΔU_{n3}	Third-harmonic neutral-point voltage variation after putting in the active arc-suppression device
C_Σ	Sum of the three-phase grounding capacitances of the system
ω	Angular frequency of the power system
ΔI_{n3}	Third-harmonic current variation of the neutral line
ΔI_{n3s}	Third-harmonic current variation of the neutral line for instantaneous faults
ΔI_{n3y}	Third-harmonic current variation of the neutral line for permanent faults
ΔU_{i3}	Injected third-harmonic voltage variation
S	Injected capacity of the dual-frequency active arc-suppression device
α	Fault position (percentage per ratio of the winding turns between the neutral point and the fault point of the stator-winding turns and the complete branch-winding turns)
θ	Phasor-angle difference between ΔI_{n3} and ΔU_{i3}

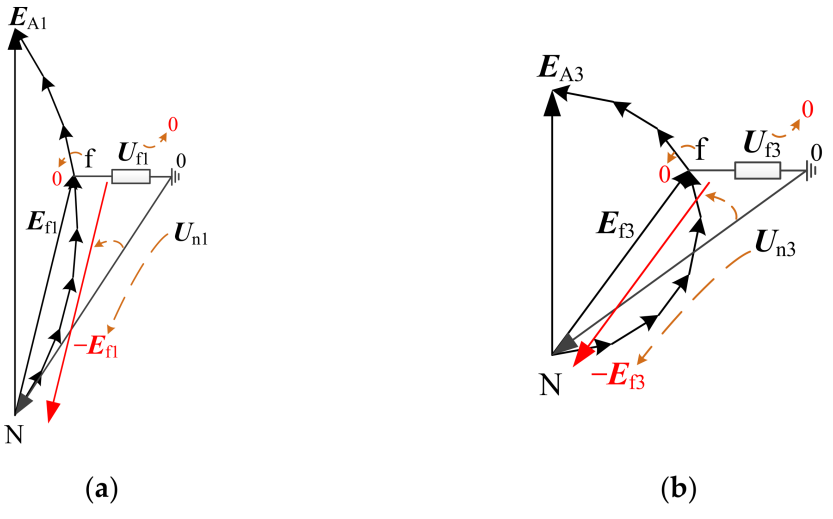


Figure 2. Phasor diagram under voltage regulation. (**a**) Phasor diagram under fundamental voltage regulation. (**b**) Phasor diagram under third-harmonic voltage regulation.

2.2. Implementation of the Hybrid Flexible Grounding Mode

2.2.1. Topology of the Active Arc-Suppression Device

For the active arc-suppression device, a voltage-based inverter is required to provide the needed compensation voltage. The related circuit topology is shown in Figure 3. The three-phase AC power source can be composed by the three-phase potential of the generator itself because the phase potential of the generator stays unchanged under single-phase ground faults. The rectifier circuit converts the introduced three-phase AC voltage into a single-phase DC voltage, and then converts it into a single-phase AC voltage by the inverter circuit. The required voltage can be output through the filtering circuit.

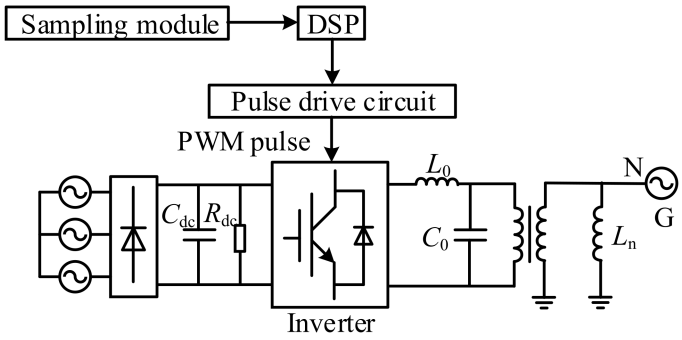


Figure 3. Topological diagram of the active arc-suppression device.

The sampling module can collect the generator neutral-point voltage. The PWM inverter adopts the double closed-loop control mode. The neutral voltage is taken as the outer-loop feedback quantity and the current is taken as the inner-loop feedback quantity. Thus, the neutral voltage can be maintained as the needed value. The literature [19–21] gives the specific control strategy and parameter design method of the control loop for the active arc-suppression technology of the distribution network. Sufficient analysis and verification has been carried out. The corresponding method can be directly applied to the dual-frequency active arc-suppression device of the generator. This paper will not give details on this.

2.2.2. Requirements of the Inverter Capacity

For large generators, the voltage level is high and the capacitive current to the ground is large. In the literature [13], the dual-frequency active arc-suppression device needs to compensate for all the fundamental and third-harmonic components in the fault current, which leads to large inverter capacity.

The neutral-point ungrounded mode during normal operation state is taken as the example. At this time, the current injected by the active arc-suppression device is the current flowing through the neutral line of the generator. Under normal operation states, the fundamental zero-sequence voltage at the neutral point is 0, and the third-harmonic voltage is $\boldsymbol{U}_{n3}$. In the process of arc suppression, the fundamental zero-sequence voltage is $-\boldsymbol{E}_{f1}$, and the third-harmonic voltage is $-\boldsymbol{E}_{f3}$. Based on the superposition theory, for each position on the stator windings after putting in the active arc-suppression device, the fundamental and third-harmonic grounding voltage variations $\Delta\boldsymbol{U}_{n1}$ and $\Delta\boldsymbol{U}_{n3}$ are:

$$\begin{aligned} \Delta\boldsymbol{U}_{n1} &= -\boldsymbol{E}_{f1} \\ \Delta\boldsymbol{U}_{n3} &= -\boldsymbol{E}_{f3} - \boldsymbol{U}_{n3} \end{aligned} \tag{3}$$

When the neutral voltage has equal amplitude and the opposite phase with the fault potential, the fault-point voltage to the ground is suppressed to 0. In the process of arc suppression, the fundamental and third-harmonic output current of the dual-frequency

active voltage arc-suppression device is equal to the grounding capacitive current of the stator windings, which can be written as follows:

$$\begin{aligned} \boldsymbol{I}_{\mathrm{i1}} &= \mathrm{j}\omega C_{\Sigma}\Delta U_{\mathrm{N1}} = -\mathrm{j}\omega C_{\Sigma}\boldsymbol{E}_{\mathrm{f1}} \\ I_{\mathrm{i3}} &= \mathrm{j}3\omega C_{\Sigma}\Delta \boldsymbol{U}_{\mathrm{N3}} = -\mathrm{j}3\omega C_{\Sigma}(\boldsymbol{E}_{\mathrm{f3}} + \boldsymbol{U}_{\mathrm{N3}}) \end{aligned} \tag{4}$$

When the fault point is close to the generator terminal, the fault potential is close to the generator phase potential. For large generators, the capacitive current is large. As a result, the fundamental and third-harmonic currents injected by the dual-frequency active arc suppression device are high. If the inverter capacity is small, it cannot provide enough arc-suppression power. Therefore, for large generators, the active arc-suppression device requires large capacity and high cost.

The above analysis applies only to generators that operate in ungrounded mode. For the generators operating in resistance-grounding mode during normal states, if the grounding resistance is not tripped during the arc-suppression process, part of the output current from the active arc-suppression device passes through the grounding resistance. Thus, the grounding resistance extinguishes part of the output power from the active arc-suppression device. In order to achieve the same arc-suppression effect, a larger-capacity inverter is needed.

To reduce the capacity of the inverter, a hybrid flexible grounding method is proposed in this paper. The generator is grounded through the arc-suppression coil during normal operation states, and the dual-frequency active arc-suppression device is put into operation after ground faults. At this point, the fundamental current injected by the inverter is:

$$\boldsymbol{I}_{\mathrm{i1}} = -\mathrm{j}(\omega C_{\Sigma} - \frac{1}{\omega L_{\mathrm{n}}})\boldsymbol{E}_{\mathrm{f1}} \tag{5}$$

Since the arc-suppression coil can compensate for most of the fundamental capacitive current, the active arc-suppression device only needs to inject the third-harmonic capacitive current and part of the fundamental current, which greatly reduces the capacity of the inverter.

3. Fault-Type Identification Method Based on Third-Harmonic Quantities

When the hybrid flexible neutral grounding mode is adopted, the arc can be eliminated and the fault current can be suppressed during single-phase ground faults. As for the instantaneous faults, the insulation of the stator windings can be recovered and the generator can be restored to the normal operating state. As for the permanent faults, after tripping the dual-frequency active arc-suppression device, the voltage at the fault point recovers and the winding insulation is broken down again. Then, the ground-fault current is regenerated, which may further damage the insulation of the generator. As a result, after the arc suppression is realized, it is necessary to distinguish transient and permanent grounding faults with effective fault-type identification strategies.

For ground faults near the neutral side of the stator winding, the fault current is mainly composed of the third-harmonic quantities. For a ground fault at the neutral point, the fault current contains only the third-harmonic component, not the fundamental component [2]. In addition, for the hybrid flexible grounding mode, the arc-suppression coil compensates for most of the fundamental component of the fault current, so if the fundamental quantities are used for fault-type identification, there is a blind area near the neutral side and the sensitivity is low. Therefore, in this paper, the third-harmonic quantities are used to identify the fault type.

In the literature [2], it is pointed out that the variation of third-harmonic voltage at any point in the generator stator windings is equal to the third-harmonic voltage variation at the neutral point. When the third-harmonic voltage applied to the neutral point is reduced,

it is assumed that the voltage variation is $\Delta \boldsymbol{U}_{i3}$. At this point, for instantaneous faults, the change of third-harmonic current $\Delta \boldsymbol{I}_{n3s}$ of the neutral line is:

$$\Delta \boldsymbol{I}_{n3s} = j3\omega C_{\Sigma} \Delta \boldsymbol{U}_{i3} \tag{6}$$

For a permanent ground fault, due to the insulation voltage recovery at the fault point, the arc re-ignites. At this time, in addition to the capacitive current to the ground, the current through the neutral line includes the resistive current flowing through the fault resistance. The third-harmonic current variation $\Delta \boldsymbol{I}_{n3y}$ of the neutral line is:

$$\Delta I_{n3y} = j3\omega C_{\Sigma} \Delta U_{i3} + \frac{\Delta \boldsymbol{U}_{i3}}{R_g} \tag{7}$$

Comparing Equations (6) and (7), the phasor diagram of the third-harmonic current variation after adjusting the third-harmonic voltage at the neutral point under different fault types is shown in Figure 4.

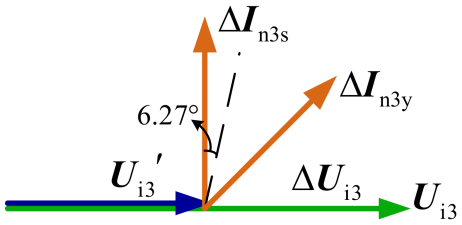


Figure 4. Phasor diagram of the third-harmonic current variation.

After changing the injected third-harmonic voltage, the fault-type identification can be realized by identifying whether the neutral current contains the resistive component. At present, in the ground-fault protection of large generators, the setting value of the fault-resistance criterion is usually set as 4 kΩ. It can be considered that the maximum value of R_g in Equation (7) is 4 kΩ. Based on the grounding capacitance parameters of the presented large generator in Section 3, the maximum phase-angle difference between $\Delta \boldsymbol{I}_{n3y}$ and $\Delta \boldsymbol{U}_{i3}$ is 83.73°. Considering a certain margin, based on the phase-angle difference between $\Delta \boldsymbol{I}_{n3}$ and $\Delta \boldsymbol{U}_{i3}$ under different fault types, the fault-type identification criterion is constructed as follows:

$$85^{\circ} \leq \arg\left(\frac{\Delta \boldsymbol{I}_{n3}}{\Delta \boldsymbol{U}_{i3}}\right) \leq 95^{\circ} \tag{8}$$

After the fault-type identification is realized, the dual-frequency active arc-suppression device can be tripped under the instantaneous fault conditions and the normal operation of the generator should be restored. For permanent fault conditions, the output voltage of the dual-frequency active arc suppression device should be restored to the initial value. Then, the loads should be smoothly transferred before the generator is tripped from the system. Thus, large-scale power failure can be avoided.

4. Simulation Verification

The parameter of a practical large nuclear generator is taken as the prototype, and a quasi-distributed parameter model is established by using PSCAD/EMTDC software to carry out the simulation analysis. Its capacity is 1278MVA, the rated voltage is 24 kV, and the rated current is 30739A. Each branch is composed of eight coils in series. The number of pole pairs is 1, the total number of slots is 48, and the corresponding slot angle is 7.5°. The grounding capacitance value of the generator stator winding is 0.397 μF per phase, and the equivalent grounding value of the equipment directly connected to the generator is 0.405 μF per phase. Take the first branch of A-phase as an example for analysis. The corresponding fundamental and third-harmonic fault potentials for when the ground fault occurs at the connection of each coil are shown in Table 2.

Table 2. Fault potential of the simulated generator.

α	$\lvert E_{f1} \rvert$/V	φ_{f1}/°	$\lvert E_{f3} \rvert$/V	φ_{f3}/°
0.125	1812.5	−52.5	449.9	22.5
0.25	3617.2	−48.75	882.6	33.75
0.375	5406.5	−45	1281.4	45
0.5	7172.6	−41.25	1630.9	56.25
0.625	8908.0	−37.5	1917.7	67.5
0.75	10,605.4	−33.75	2130.9	78.75
0.875	12,257.5	−30	2262.1	90
1	13,856.3	−26.25	2306.4	101.25

In Table 2, $\lvert E_{f1} \rvert$ and $\lvert E_{f3} \rvert$ mean the amplitudes of the fault potential, and φ_{f1} and φ_{f3} mean the phase angles of the fault potential. The fundamental and third-harmonic potentials corresponding to each coil turn in Table 2 are calculated based on the practical distribution coefficient and the short-range coefficient of the stator windings. Based on the data in Table 2, the quasi-distributed parameter model can be established to simulate and analyze the ground faults at different fault positions.

4.1. Verification of the Arc-Suppression Effect

To verify the arc-suppression effect of the proposed hybrid flexible grounding mode, a single-phase ground fault was set at 0.2 s, the fault position was set at the generator terminal (α = 1), and the grounding transition resistance was set as 500 Ω. For the dual-frequency active arc-suppression part, a fundamental voltage with an amplitude of 13856.3 V and a phase of 153.75° was injected into the generator neutral point at 0.24 s. Simultaneously, a third-harmonic voltage with an amplitude of 2306.4V and a phase of −78.75° was injected. The ground-fault current simulation results under ungrounded mode, grounding through the arc-suppression coil mode, dual-frequency active arc-suppression mode, and hybrid flexible grounding mode are shown in Figure 5.

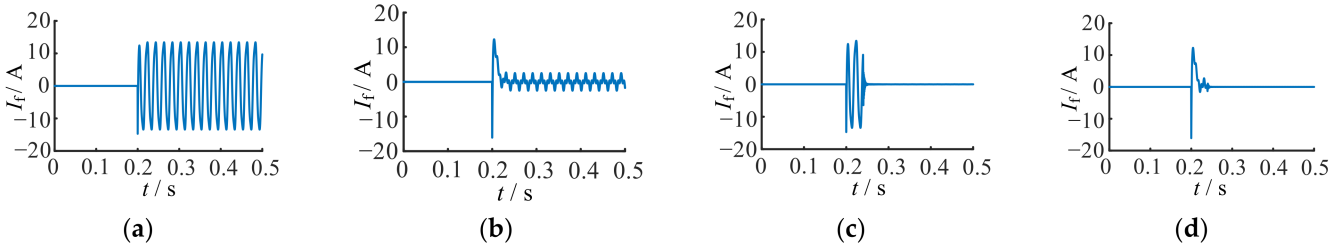


Figure 5. Fault-current simulation results under different grounding modes. (**a**) Ungrounded mode; (**b**) grounding through the arc-suppression coil mode; (**c**) dual-frequency active arc-suppression mode; (**d**) hybrid flexible grounding mode.

In Figure 5, the arc-suppression coil-grounding mode corresponds to the overcompensation condition, and the compensation degree was 10%. In the case of dual-frequency active arc-suppression mode, the neutral point was ungrounded in normal operation states, and the dual-frequency active arc-suppression device was put in at 0.24 s. In the case of hybrid flexible grounding mode, the overcompensation degree of the arc suppression coil was 10%. The neutral point was grounded through the arc-suppression coil under normal operation states, and the dual-frequency active arc-suppression device was put in at 0.24 s. The simulation results show that if the neutral point was ungrounded, the fault current was high, which was detrimental to the safety of the generator. As for the arc-suppression coil-grounding mode, although the fault current was suppressed, effective arc extinguishing could not be realized. When the dual-frequency active arc-suppression device was connected, effective arc extinguishing could be realized and the fault current

was suppressed to 0. For the hybrid flexible grounding mode, the arc-suppression coil suppressed part of the fault current at the initial fault time, so the steady-state value of the ground-fault current after fault was low, which was conducive to the safety of the stator iron core.

For the proposed hybrid flexible grounding method, simulation analysis was carried out under different fault scenarios. Table 3 shows the simulation results of the fault point voltage and the ground-fault current after the dual-frequency active arc-suppression device was put into operation.

Table 3. Arc-suppression effect under different fault scenarios.

Fault Scenario		U_f /V	I_f /V
α	R_g/Ω		
0	50	7.22	0.14
	500	7.22	0.01
	Cassie	7.84	0
0.125	50	4.77	0.06
	500	4.77	0.01
	Cassie	4.77	0
0.25	50	5.15	0.07
	500	5.16	0.01
	Cassie	5.15	0
0.375	50	5.25	0.07
	500	5.26	0.01
	Cassie	5.25	0
0.5	50	5.05	0.07
	500	5.06	0.01
	Cassie	5.06	0
0.625	50	4.60	0.07
	500	4.61	0.01
	Cassie	4.61	0
0.75	50	4.12	0.07
	500	4.12	0.01
	Cassie	4.13	0
0.875	50	3.88	0.07
	500	3.89	0.01
	Cassie	3.89	0
1	50	3.43	0.07
	500	3.43	0.01
	Cassie	3.44	0

In Table 3, the constant resistance model and Cassie arc model are respectively used to simulate the fault resistance. The Cassie arc model believes that the arc energy generation and dissipation are both proportional to the arc-crossing section, which is commonly used in arc simulation and can simulate the nonlinear characteristics of the arc [22]. The simulation results show that the hybrid flexible grounding method could effectively suppress the fault-point voltage at different fault locations and fault resistances. The ground-fault current could be effectively suppressed and effective arc extinguishing could be realized. The proposed method can avoid damage to the generator stator iron core caused by the ground-fault current.

4.2. Simulation Analysis of the Inverter Capacity

In order to prove that the proposed hybrid flexible grounding method can reduce the inverter capacity compared with the existing method, the needed capacity under

different fault conditions was simulated and analyzed. Since the dual-frequency active arc-suppression device was adopted, the injected capacity included fundamental and third-harmonic components, and the calculation formula of the capacity S is:

$$S = U_{i1} I_{i1} + U_{i3} I_{i3} \tag{9}$$

Table 4 shows the output capacity simulation results under different fault conditions. The needed capacity under the proposed hybrid flexible grounding mode was compared with the dual-frequency active arc-suppression device alone.

Table 4. Inverter capacity simulation results under different fault scenarios.

Fault Scenario				**Injected Quantities of the Inverter**					
α	R_g/Ω	U_{i1}/V	U_{i3}/V	**Dual-Frequency Active Arc-Suppression Mode**			**Hybrid Flexible Grounding Mode**		
				I_{i1}/A	I_{i3}/A	S/kVA	I_{i1}/A	I_{i3}/A	S/kVA
0	50	0	10	0	4.01	0.04	0	4.01	0.04
	500			0	4.02	0.04	0	4.02	0.04
	Cassie			0	4.01	0.04	0	4.00	0.04
0.125	50	1812.5∠127.5	449.9∠−157.5	1.36	3.75	4.16	0.13	3.77	1.94
	500			1.37	3.75	4.17	0.14	3.76	1.94
	Cassie			1.37	3.75	4.16	0.14	3.77	1.94
0.25	50	3617.2∠131.25	882.6∠−146.25	2.73	3.34	12.83	0.27	3.37	3.96
	500			2.73	3.35	12.85	0.28	3.36	3.97
	Cassie			2.72	3.34	12.84	0.28	3.37	3.96
0.375	50	5406.5∠135	1281.4∠−135	4.09	2.83	25.73	0.40	2.84	5.84
	500			4.08	2.82	25.72	0.41	2.84	5.84
	Cassie			4.09	2.84	25.73	0.40	2.84	5.85
0.5	50	7172.6∠138.75	1630.9∠−123.75	5.42	2.24	42.56	0.53	2.22	7.48
	500			5.43	2.24	42.56	0.53	2.23	7.49
	Cassie			5.41	2.25	42.58	0.53	2.22	7.48
0.625	50	8908.0∠142.5	1917.7∠−112.5	6.73	1.63	63.14	0.67	1.52	8.87
	500			6.73	1.62	63.15	0.68	1.52	8.87
	Cassie			6.72	1.63	63.14	0.67	1.54	8.88
0.75	50	10605.4∠146.25	2130.9∠−101.25	8.01	1.16	87.53	0.79	0.81	10.18
	500			8.00	1.16	87.52	0.79	0.80	10.18
	Cassie			8.01	1.17	87.54	0.79	0.82	10.19
0.875	50	12257.5∠150	2262.1∠−90	9.26	1.11	116.13	0.92	0.48	12.38
	500			9.25	1.12	116.12	0.93	0.49	12.40
	Cassie			9.26	1.10	116.13	0.92	0.50	12.39
1	50	13856.3∠153.75	2306.4∠−78.75	10.48	1.53	148.73	1.03	1.05	16.81
	500			10.48	1.53	148.73	1.04	1.08	16.83
	Cassie			10.50	1.52	148.72	1.04	1.07	16.83

In Table 4, for the ground faults at the neutral point of the generator, only the third-harmonic voltage existed and there was no fundamental voltage at the fault point. Therefore, only a lower-value third-harmonic voltage was injected. The amplitude of the injected third-harmonic voltage in this paper was 10 V. The injected capacity in the table is the sum of fundamental and third harmonic capacities injected by the dual-frequency active arc-suppression device. For the case in which only the dual-frequency active arc-suppression device was used, the closer the fault point was to the generator terminal, the higher the fundamental voltage to be injected and the higher the fundamental current to be output by the inverter. Accordingly, the larger capacity should be provided, and the capacity of the inverter should be at least 150 kVA. For the hybrid flexible grounding method proposed in

this paper, since the arc suppression coil could compensate for most of the fundamental components, the fundamental current output by the inverter was greatly reduced. The capacity of the inverter only needed about 20 kVA, which could greatly reduce the volume and cost of the active arc-suppression device.

4.3. Verification of the Proposed Fault-Type Identification Method

When identifying the fault type, it is necessary to adjust the third-harmonic voltage injected by the dual-frequency active arc suppression device. In this process, the voltage phase remains unchanged and the amplitude is adjusted to half of the previous value. To verify the effectiveness of the proposed method, transient and permanent grounding faults for different fault scenarios were set. The phase angle difference between $\Delta \boldsymbol{I}_{n3}$ and $\Delta \boldsymbol{U}_{i3}$ is shown in Table 5.

Table 5. Fault-type identification results under different fault scenarios.

Fault Scenario		$\boldsymbol{\theta}$/°	
$\boldsymbol{\alpha}$	$\boldsymbol{R_g}$/Ω	**Transient**	**Permanent**
0	50	85.42	2.16
	500	85.69	10.75
	Cassie	85.52	6.79
0.125	50	85.48	13.48
	500	85.74	21.56
	Cassie	86.90	17.27
0.25	50	87.13	19.53
	500	87.92	21.36
	Cassie	87.54	20.67
0.375	50	87.98	22.05
	500	88.82	23.16
	Cassie	88.06	22.67
0.5	50	89.08	25.56
	500	89.24	28.35
	Cassie	89.18	27.33
0.625	50	89.22	30.18
	500	89.54	33.55
	Cassie	89.37	32.48
0.75	50	89.78	38.71
	500	89.84	40.42
	Cassie	89.79	39.41
0.875	50	89.90	43.56
	500	89.94	45.14
	Cassie	89.91	44.12
1	50	89.91	51.45
	500	89.92	54.15
	Cassie	89.90	52.81

In Table 5, the phase angles of the phasors were solved by Fourier transform. The simulation results show that under transient fault conditions, since the neutral current only contained the capacitive components, the phase-angle difference met the criterion of Equation (8). Under the condition of permanent fault conditions, the neutral current contained a certain resistive component, and the phase-angle difference did not meet the criterion of Equation (8). On this basis, the fault-type identification could be reliably realized.

5. Dynamic Test Verification

The quasi-distributed parameter model could only reflect the structural characteristics of the generator stator windings, but could not reflect the demagnetization effect of the load to the generator potential and the excitation regulation characteristics of the generator. Therefore, it could only be verified that the proposed method was effective under the no-load operation. However, it could not be verified that the proposed method was suitable for different operating conditions. To fully verify the effectiveness of the proposed method, experimental tests were carried out on a dynamic model generator. The capacity of the generator was 15 kVA, and the rated voltage was 400 V. It adopted the arc-suppression coil neutral grounding mode, and the compensation degree was 10%. A programmable AC power source was used to simulate the dual-frequency active arc suppression device. It could output voltages of different frequencies at the same time. The voltage amplitude adjustment range was 0~300 V, the phase-adjustment range was −180°~+180°, and the frequency-adjustment range was 15~1600 Hz. The experimental system could be used to verify the hybrid flexible grounding method.

The wiring diagram of the dynamic experimental system is shown in Figure 6, and the photo is shown in Figure 7.

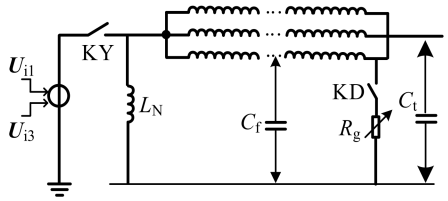


Figure 6. Wiring diagram of the dynamic experimental system.

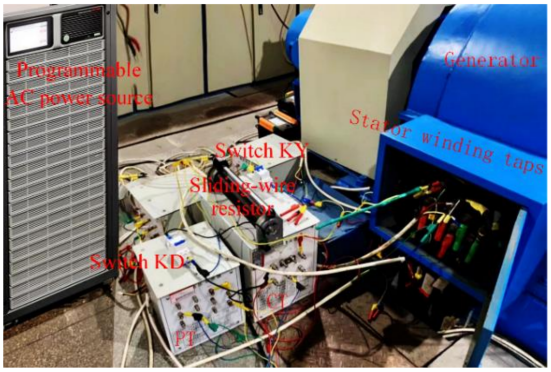


Figure 7. A photo of the dynamic experimental system.

Taking the single-phase ground fault at the generator terminal of the A-phase as an example, the fault potential was equal to the A-phase potential. Under the no-load operation condition, the fundamental and third-harmonic phase potentials were measured online. Based on Fourier transform, the amplitudes and phase angles were 222.69 V∠−44.25° and 2.91 V∠123.75°, respectively. The output voltage of the programmable AC power supply were set to be equal in amplitude and opposite in phase to the fault potential. During the experimental test process, the switch KD between the generator terminal and the sliding-line resistor was used to set the ground fault, and the switch KY between the programmable AC power supply and the generator neutral point was used to input the dual-frequency active arc-suppression device. The resistance of the sliding-line resistor was regulated to 200 Ω. In this process, the waveforms of the fault-point voltage and the ground-fault current are shown in Figure 8a.

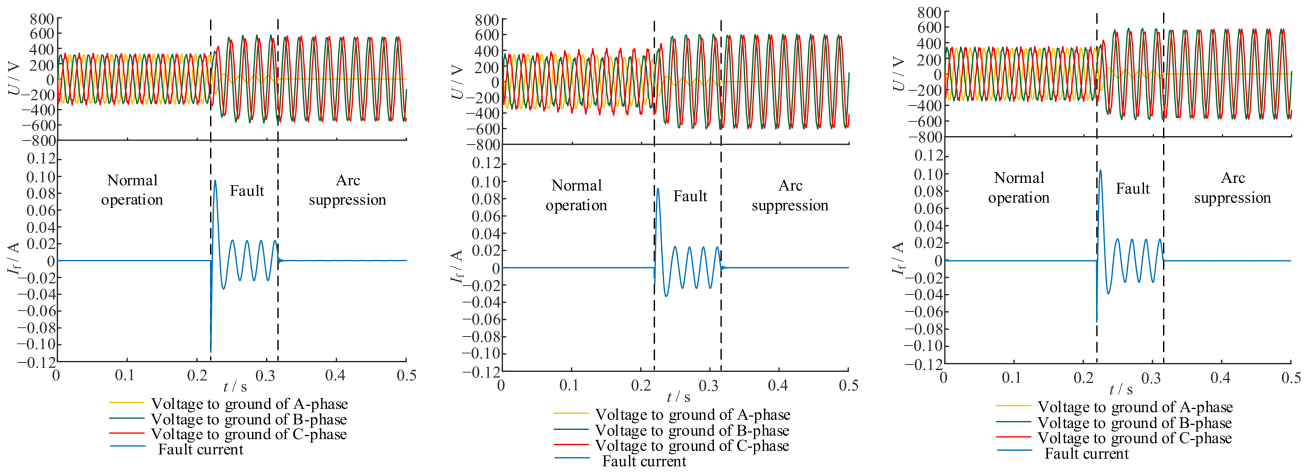


Figure 8. Experimental results of arc suppression. (**a**) No-load condition; (**b**) 50% load condition; (**c**) 100% load condition.

After putting in the dual-frequency active arc-suppression device, the fault-point voltage was reduced to 0.14 V and the fault current was suppressed to 0. Due to the neutral voltage regulation, the non-fault phase voltage at the generator terminal rose to the line voltage. Since the system insulation is usually designed according to the line voltage level, it did not affect the insulation safety. The experiment was repeated under the load conditions of 50% and 100%. Under the 50% load condition, influenced by the load demagnetization and the excitation regulation, the amplitudes and phase angles of the fundamental and third-harmonic phase potentials changed to 239.05 V$\angle -17.12°$ and 4.76 V$\angle -163.18°$, respectively. Under the 100% load condition, the amplitudes and phase angles of the fundamental and the third-harmonic phase potentials were 230.16 V$\angle -26.25°$ and 7.28 V$\angle 101.25°$, respectively. The output voltage of the programmable AC power supply was set with equal amplitude and the opposite phase of the phase potential, and the arc-suppression results are shown in Figure 8b,c. The test results show that the proposed method was not affected by the operating conditions and the generator excitation regulation.

To verify the effectiveness of the proposed fault-type identification method under different operating conditions, after the completion of arc suppression, the injected fundamental voltage was controlled unchanged, and the injected third-harmonic voltage was changed to make its amplitude half of before. For instantaneous faults, before changing the injected voltage, the switch KD was cut off, so the faulty branch was removed. For permanent faults, the faulty branch was always reserved. Corresponding to different load conditions, Fourier transform was used to calculate the phase-angle difference between $\Delta \boldsymbol{I}_{n3}$ and $\Delta \boldsymbol{U}_{i3}$. The calculation results are shown in Table 6.

Table 6. Fault-type identification test results under different fault scenarios.

Operation Mode	θ/°	
	Transient	**Transient**
No-load condition	88.22	42.16
50% load condition	87.96	40.79
100% load condition	87.52	40.75

In Table 6, the phase-angle differences of the phasors were solved by Fourier transform. The experimental calculation results shown in Table 6 show that the phase-angle difference between $\Delta \boldsymbol{I}_{n3}$ and $\Delta \boldsymbol{U}_{i3}$ was approximately 90° under transient fault conditions, which meets the criterion of Equation (8). However, the criterion of Equation (8) was not satisfied

under the condition of permanent faults. The proposed method can effectively identify the transient and permanent ground faults without being affected by the load condition and excitation regulation.

6. Conclusions

In order to reduce the inverter capacity of the existing dual-frequency active arc-suppression device, a novel hybrid flexible neutral grounding mode for large generators is proposed, which combines the active arc-suppression strategy with the arc-suppression coil-grounding mode. The following conclusions were drawn.

(1) The hybrid flexible grounding method achieved reliable arc suppression. Simulation results verify that it was not affected by the fault position or the grounding transition resistance. Experimental results verify that it was not affected by the system-operating condition and the generator excitation regulation.

(2) Because the arc-suppression coil could compensate for most of the fundamental components, the fundamental current injected by the dual-frequency active arc-suppression device was greatly reduced. The capacity of the inverter only needed about 20 kVA, which greatly reduced the volume and the cost.

(3) For instantaneous ground faults, the phase-angle difference between the third-harmonic voltage and current variation at the generator neutral point was close to 90°. For permanent ground faults, the above relation could not be satisfied since the neutral line current contained certain resistive components. Under different fault scenarios, according to Equation (8), the fault type identification could be reliably realized.

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References

1. Fulczyk, M.; Bertsch, J. Ground fault currents in unit-connected generators with different elements grounding neutral. *IEEE Trans. Energy Convers.* **2002**, *17*, 61–66. [CrossRef]
2. Wang, Y.K.; Yin, X.G.; Qiao, J.; Tan, L.M.; Xu, W.; Li, W. Generator stator windings ground fault diagnosis for generator–grid directly connected system of floating nuclear power plant. *Energy Rep.* **2021**, *7*, 460–469. [CrossRef]
3. Wu, A.Y. MV Generator Ground Fault Arcing Power Damage Assessment. *IEEE Trans. Ind. Appl.* **2018**, *54*, 912–915. [CrossRef]
4. Tai, N.L.; Stenzel, J. Differential protection based on zero-sequence voltages for generator stator ground fault. *IEEE Trans. Power Del.* **2007**, *22*, 116–121.
5. Yin, X.G.; Malik, O.P.; Hope, G.S.; Chen, D.S. Adaptive ground fault protection schemes for turbogenerator based on third harmonic voltages. *IEEE Trans. Power Del.* **1990**, *5*, 595–603. [CrossRef]
6. Safari-Shad, N.; Franklin, R.; Negahdari, A.; Toliyat, H.A. Adaptive 100% Injection-Based Generator Stator Ground Fault Protection with Real-Time Fault Location Capability. *IEEE Trans. Power Del.* **2018**, *33*, 2364–2372. [CrossRef]
7. Ding, W.L.; Luo, J.; Li, J. Stator Ground Fault Protection of Direct Generator-Bus Connection. *Autom. Elect. Power Syst.* **2007**, *31*, 74–78.
8. Gulachenski, E.M.; Courville, E.W. New England Electric's 39 years of experience with resonant neutral grounding of unit-connected generators. *IEEE Trans. Power Del.* **1991**, *6*, 1016–1024. [CrossRef]
9. Jia, W.C.; Cao, S. Parameter optimization design of combination-type grounding mode for large-sized hydropower units. *Elect. Power Autom. Equip.* **2022**, *4*, 79–85.

10. Yin, X.G.; Wang, Y.K.; Li, P.; Xu, W.; Wu, D.L.; Qiao, J.; Liu, X.Y. Study on security problems and protection technologies of the floating nuclear power plant grid. *Power Syst. Prot. Cont.* **2020**, *48*, 9–17.
11. Burgess, R.; Ahfock, A. Minimising the risk of cross-country faults in systems using arc suppression coils. *IET Gene. Trans. Distr.* **2011**, *5*, 703–711. [CrossRef]
12. Yu, K.; Liu, Z.L.; Zeng, X.J.; Li, J.Z.; Yang, L. A novel full compensation method for the ground fault current of resonant grounded systems. *Electr. Eng.* **2021**, *103*, 1569–1581. [CrossRef]
13. Wang, Y.K.; Yin, X.G.; Xu, W.; Qiao, J.; Tan, L.M. Active Arc Suppression Algorithm for Generator Stator Winding Ground Fault in the Floating Nuclear Power Plan. *IEEE Trans. Power Del.* **2022**, *early access*.
14. Friedemann, D.F.; Motter, D.; Oliveira, R.A. Stator-Ground Fault Location Method Based on Third-Harmonic Measures in High-Impedance Grounded Generators. *IEEE Trans. Power Del.* **2021**, *36*, 794–802. [CrossRef]
15. Rifaat, R.M. Utilizing third harmonic 100% stator ground fault protection, a cogeneration experience. *Proc. IEEE Conf. Ind. Appl.* **2000**, *5*, 3254–3259.
16. Xiong, B.; Zhou, L.; Ding, S. Study on Dynamic Characteristics of Single-Phase Grounding Fault of 1000 MW Hydro Generator under Different Grounding Modes. *Machines* **2022**, *10*, 554. [CrossRef]
17. Powell, L.J. Stator Fault Damage Considerations for Generators on Solidly Grounded Systems. *IEEE Trans. Ind. Appl.* **2001**, *37*, 218–222. [CrossRef]
18. Yao, H.N.; Cao, M.Y. *Power System Resonance Grounding Theory*; China Electric Power Press: Beijing, China, 2009; pp. 40–45.
19. Wang, W.; Zeng, X.J.; Yan, L.J.; Xu, X.Y.; Guerrero, J.M. Principle and Control Design of Active Ground-Fault Arc Suppression Device for Full Compensation of Ground Current. *IEEE Trans. Ind. Electron.* **2017**, *64*, 4561–4570. [CrossRef]
20. Fan, B.S.; Yao, G.Z.; Yu, K.; Zeng, X.J.; Wang, W.; Zhuo, C.; Guerrero, J.M. Principle of Flexible Ground-Fault Arc Suppression Device Based on Zero-Sequence Voltage Regulation. *IEEE Access* **2020**, *9*, 2382–2389. [CrossRef]
21. Fan, B.S.; Yao, G.Z.; Wang, W.; Zeng, X.J.; Guerrero, J.M.; Yu, K.; Zhuo, C. Principle and Control Design of a Novel Hybrid Arc Suppression Device in Distribution Networks. *IEEE Trans. Ind. Electron.* **2022**, *69*, 41–51. [CrossRef]
22. Xu, X.Z.; Hu, W.G. Modeling and simulation of arc grounding fault of middle and low voltage distribution network based on ATP-EMTP. *J. Comput. Methods Sci. Eng.* **2020**, *20*, 1279–1288. [CrossRef]