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A novel high-impedance neutral grounding method for medium- or large-size hydroelectric generators

Jianming Jiang[1] | **Xu Jiang**[2] | **Gongyi Song**[1] | **Song Tong**[3] | **Yanhai Li**[3]

[1]China Energy Science and Technology Research Institute Co.,Ltd. Chengdu Branch, Chengdu, Sichuan, China

[2]Institute for Energy and Environment, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK

[3]Chinese Energy Tibet Niyang River Hydropower Development Co. Ltd, Chengdu, China

Correspondence
Jianming Jiang, China Energy Science and Technology Research Institute Co., Ltd. Chengdu Branch, Chengdu, Sichuan 610091, China.
Email: iyb13133@gmail.com

Abstract

As the capacity of medium or large hydroelectric generators increases, conventional grounding methods face challenges in effectively limiting single-phase to earth fault current and neutral displacement voltage within acceptable range. Excessive fault current and neutral displacement voltage pose threats to the stability and safety of power generation and transmission systems. Inherent design deficiencies in conventional grounding methods lead to failures in meeting fault current and voltage requirements. To address this, this paper proposes a novel grounding method utilizing high impedance to restrict excessive fault current and neutral displacement voltage. The method minimizes both fault current and neutral displacement voltage by optimally selecting device parameters through minimal iterative trials. Additionally, a novel indicator is introduced to evaluate the effectiveness of grounding method by monitoring changes in neutral displacement voltage. The method is tested through theoretical calculation and field experiments, successfully implemented in large-size hydroelectric generator.

1 | INTRODUCTION

As industrial loads increase, the operational capacities of hydroelectric generators correspondingly rise. Additionally, increased direct-fed loads have been connected directly to the generators, and supplementary capacitors have been installed at the generator outlet circuit breaker terminals to mitigate overvoltage conditions. These additions can cause a significant increase in capacitive current (the maximum permissible capacitive current for neutral grounding methods is 15 A [1]) and result in excessive single-phase to earth fault current, potentially posing a threat to generator safety and stability [2, 3]. Conventional neutral grounding methods are employed to address this issue. However, they are afflicted by either excessively high single-phase to earth fault current or elevated neutral displacement voltage [4], representing hazards to medium- and large-scale hydroelectric generators. For instance, if the capacitive current exceeds the tolerable threshold for an extended duration, it can lead to stator core burnout and compromise the insulation integrity of the stator winding [5].

The conventional neutral grounding methods can be categorized into three distinct types: solid grounding, arc suppression grounding (ASG), and high-resistance grounding (HRG). The selection of the appropriate method is contingent upon multiple factors, including the system's scale, voltage level, and the specific protection schemes employed. Solid grounding is typically implemented for hydroelectric generators with relatively small capacities. However, as the generator capacity increases, exceedingly high single-phase to earth fault current may be generated, potentially inflicting damage to the generator. Consequently, larger hydroelectric generators transitioned to ASG [5], a neutral grounding method that can partially mitigate single-phase to earth fault current by compensating for the capacitive current component. Nonetheless, as industrial loads continued to proliferate, maintaining the capacitive current within an acceptable long-term limit became increasingly challenging when employing ASG. Furthermore, ASG intrinsically contributes to an increase in the neutral displacement voltage, potentially compromising generator safety and inducing malfunctions in the protection system. To curtail the neutral displacement voltage, a subset of hydroelectric generators adopted HRG in their neutral grounding systems [6]. However, HRG invariably leads to an escalation in single-phase to earth fault current, jeopardizing the generator. In summation, conventional neutral grounding

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methods can only effectively limit either single-phase-to-ground fault current or neutral displacement voltage, failing to concurrently satisfy both requirements. This deficiency exposes medium- and large-scale hydroelectric generators to potential risks.

To address the challenges posed by high single-phase to earth fault current or elevated neutral displacement voltage arising from increased generator capacities, numerous studies have been undertaken. Reference [7] utilized inductive current generated by the transformer's intrinsic reactance to partially compensate for the fault capacitance current. Reference [8] demonstrated three distinct fault detection and protection schemes to mitigate the hazards associated with excessive fault current. Reference [9] examined the limitations of HRG and optimized the design to reduce the impact of capacitive current. Reference [10] developed a high-fidelity fault simulation model tailored for high-capacity hydroelectric generators and employed it to determine optimal parameters for various neutral grounding methods. Reference [11] proposed an injected current regulation-based stator ground fault arc suppression method to constrain the fault point voltage to a low level. However, none of these studies successfully achieved simultaneous limitation of both single-phase-to-ground current and neutral displacement voltage. This paper, therefore, proposes a novel high-impedance method that can confine both the single-phase-to-ground fault current and neutral displacement voltage within acceptable ranges through an innovative grounding method design. Furthermore, this paper furnishes a parameter calculation method to enhance the design efficiency. The key innovations presented in this paper are: (1) the introduction of a novel indicator, the displacement voltage coefficient (DVC), to generically quantify the risk level associated with neutral displacement voltage. While the neutral displacement voltage is an absolute value, rendering it challenging to reflect the degree of neutral voltage variation induced by the incorporated grounding instruments, the proposed coefficient can intuitively indicate this attribute. (2) The formulation of a parameter optimization method to determine the optimal parameters for the high-impedance neutral grounding system. (3) The proposed high-impedance method can concurrently limit both neutral displacement voltage and single-phase to earth fault current, enabling seamless implementation in large-scale hydroelectric generators.

This paper is structured as follows: The next section outlines the challenges faced by large- or medium-sized hydroelectric generators. Then, an overview of conventional neutral grounding methods applied in hydroelectric generators is provided, highlighting the limitations of these methods and the potential consequences for generators when the single-phase to earth fault current is excessive. Subsequently, the key parameters of the proposed method are detailed, including their acceptable ranges. The following section introduces a parameter optimization method for the proposed grounding technique. A case study is then presented, exploring the practical application of the proposed method. The paper concludes with a discussion on the significance of the contributed technique for large- and medium-sized hydroelectric generators.

2 | PROBLEM STATEMENT

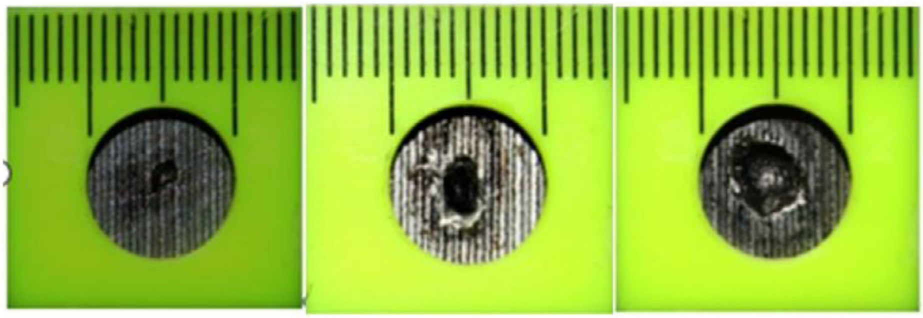
In the last decade, faults have become more frequent in large- or medium-sized hydroelectric generators due to the inappropriate selection of grounding systems. In Sichuan, the capacitive currents of seven hydroelectric generators increased after renovations, yet they continued to employ ASG. This resulted in the grounding currents exceeding the permissible range, and the off-tuning degree surpassing the required limit. It was also observed that the stator winding insulation of a hydroelectric generator was upgraded from class B to class F, but the ASG method was retained. Consequently, the stator grounding protection was activated during the no-load voltage rise of the starting machine (set value 8 V). Although the neutral point of the generator was temporarily connected to a slip wire resistance to simulate a HRG method, and the slip wire resistance was adjusted under a no-load model, it was still not possible to control the current below the permissible value. From these observations, the fault current could reach more than 80 A for large-sized hydroelectric generators. To further explore the impact of excessive current, experiments were designed and conducted specifically to simulate different levels of single-phase to earth fault currents on the iron core [5], and the results are as follows.

First, a single-phase-to-ground fault current of 19.4 A was observed on a hydroelectric generator, whose stator ground fault clearance time was 0.6 s. This event caused a moderate degree of damage to the stator core, resulting in the fusion of approximately eight pieces of the iron core, forming a melting crater with a length of about 5 mm, a width of about 3 mm, and a depth of approximately 1.3 mm. Subsequently, an event involving a single-phase grounding current of less than 10 A was designed to observe its impact, and minor damage was observed in Figure 1a. However, when the fault current exceeded 25 A, severe damage was observed on the stator core. Therefore, upgraded large-capacity hydroelectric generators are exposed to a high risk of single-phase fault events.

3 | CONVENTIONAL NEUTRAL GROUNDING METHODS FOR HYDROELECTRIC GENERATORS

The neutral grounding system is multifaceted, as it is related to various factors such as the voltage level, single-phase to earth fault current, neutral displacement voltage, and the protection system. Three components are included: stator windings, grounding instruments, and capacitance-to-ground. The equivalent circuit diagram of the grounding system is presented in Figure 2.

As shown in Figure 2, the capacitance-to-ground is normally represented by distributed capacitors. However, distributed capacitors are complex to analyse. To simplify this, this paper uses a centralized capacitor to represent the capacitance-to-ground (in the black dashed box) and connects it to the end of the stator windings. The grounding instrument in the blue



(a) Minor damage to stator core (b) Moderate damage to stator core (c) Serious damage to the stator core

(fault current <10A) (fault current 10A – 25A) (fault current > 25A)

FIGURE 1 Stator core damage due to inappropriate grounding system selection.

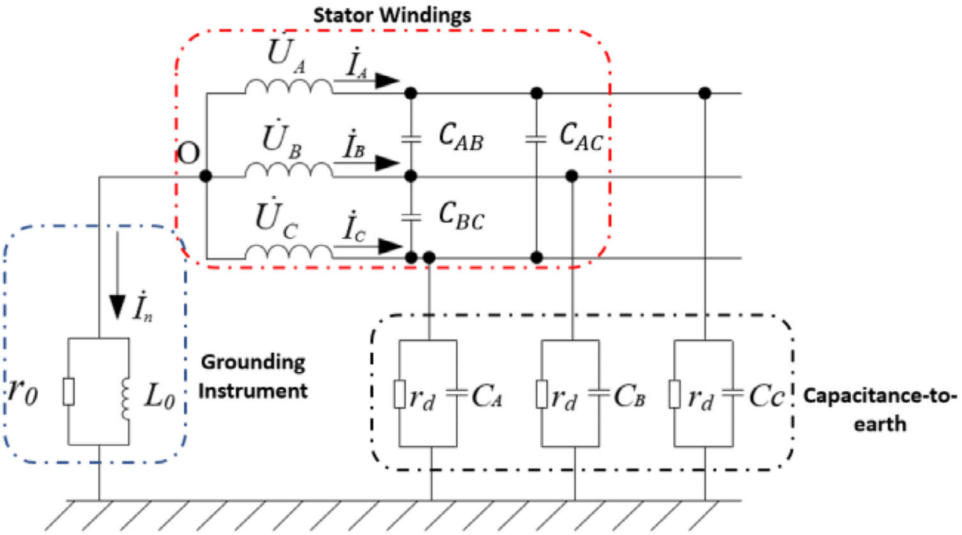


FIGURE 2 A generic diagram for neutral grounding system of hydroelectric generators. r_0: equivalent primary resistance; L_0: equivalent primary reactance; r_d: resistance-to-ground; C_A, C_B, C_C: capacitance-to-ground; C_{AB}, C_{BC}, C_{CA}: phase-to-phase capacitance; $\dot{U}_A, \dot{U}_B, \dot{U}_C$: single phase voltage.

dashed line box can be represented as an impedance. The equivalent circuit diagram in the red dashed box represents the stator windings. Figure 2 is applicable to all grounding systems, including solid grounding, ASG, and HRG.

To assess the performance of different grounding methods, the following metrics are typically used: single-phase earth fault current (I_k), unbalanced voltage (U_{bd}), and displacement voltage (U_0). The unbalanced voltage of a generator is the neutral-to-ground voltage at the rated voltage when the neutral of the generator is not connected to a grounding instrument; the neutral displacement voltage of a generator is the same voltage measured when connected to a grounding instrument. Theoretically, when the three-phase capacitances-to-ground are identical, the unbalanced voltage should be zero. In reality, it is impossible to achieve identical capacitances for the three windings due to uncertainties in insulation thickness, winding length, and materials, among other factors. Therefore, voltage imbalance is unavoidable. To comprehensively evaluate the performance of grounding methods, a comparison of unbalanced voltage and neutral displacement voltage is required—with a grounding instrument connected, the neutral voltage would shift, which may cause the voltage to exceed the permitted range. This paper introduces a new indicator called the DVC to directly quantify the impact of the grounding method by comparing the unbalanced voltage and neutral displacement voltage:

$$\mathrm{DVC} = \frac{|U_0|}{\lceil U_{bd} \rceil} \tag{1}$$

The DVC is the ratio of the magnitude of the displacement voltage to the magnitude of the unbalanced voltage. This ratio is a relative value, which allows it to be used for hydroelectric generators of different scales. Through trials and experimentation, it has been determined that the DVC should be less than 1.5 for all grounding devices, considering the impact on power quality [5]. Ideally, the DVC is expected to be as small as possible to minimize the impact on power quality.

According to Figure 2, the generic displacement voltage and single phase to earth fault current can be expressed as

$$\dot{U}_0 = -\frac{j\omega\left(C_A+\alpha^2 C_B+\alpha C_C\right)}{\left(\frac{3}{r_d}+\frac{1}{r_0}\right)+\left[j\omega\left(C_A+C_B+C_C\right)-j\frac{1}{\omega L_0}\right]}\dot{U}_A \quad (2)$$

$$I_k = \frac{U_N}{\sqrt{3}} * \sqrt{\left(\frac{1}{r_0}\right)^2+\left(\omega\left(C_A+C_B+C_C\right)-\frac{1}{\omega L_0}\right)^2} \quad (3)$$

where a phasor rotation operator α, which rotates a phasor vector counterclockwise by 120 degrees when multiplied by it; ω donates the angular speed which is 314 rad/s; U_N represents the rated voltage. For the solid grounding method, the grounding instruments are equivalent open circuit—the resistance r_0 and reactance L_0 are infinite, and the displacement voltage will be equivalent to the unbalanced voltage. In terms of ASG and HRG, the grounding instrument of both can be equivalent to a RL parallel circuit.

4 | HIGH IMPENDENCE GROUNDING METHOD

The solid grounding method is prone to generating arcs during single-phase to earth faults; the ASG is prone to over-compensation or full compensation of the capacitive current, which would result in high neutral displacement voltage during generator operation; the HRG is prone to excessive single-phase to earth fault current during generator operation. Therefore, none of the traditional grounding methods can meet the needs of large- and medium-sized hydroelectric generators. To address this, this paper proposes a High-Impedance Grounding (HIG) method. This method can solve the problems of excessive neutral displacement voltage and single-phase to earth fault current in large-capacity hydroelectric generators. The HIG method also utilizes a parallel RL circuit whose resistance and inductance can be smoothly adjusted, and the adjustment range is sufficiently large to accommodate the requirements of medium and large hydroelectric generators. The equivalent circuit diagram of the HIG method is presented in Figure 3.

The resistance and inductance on the secondary side of the transformer are adjustable devices, which allows the HIG method to be utilized for different scenarios. As long as the resistance and inductance are properly selected, the high-impedance RL circuit can effectively reduce either the single-phase to earth fault current, the arc overvoltage, or the neutral voltage. The selection of resistance and inductance values typically depends on various factors, such as the capacitive current, neutral-to-ground current, single-phase to earth fault current, neutral displacement voltage, arc overvoltage, and the ratio of resistance to inductance (RoRI). To explore these factors, an equivalent circuit diagram of the HIG during a single-phase-to-ground fault is presented in Figure 4.

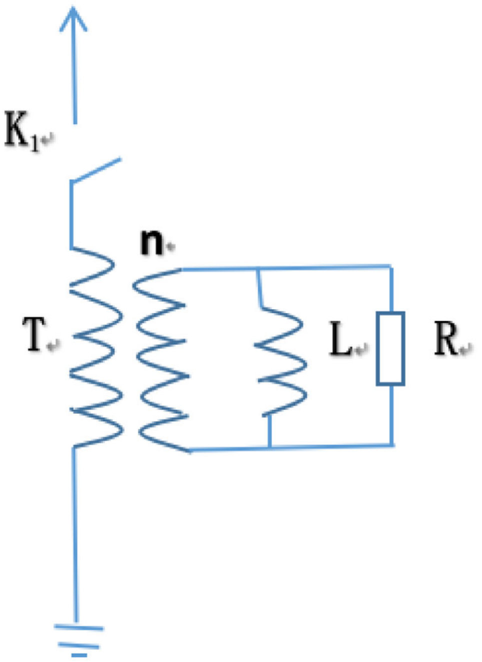


FIGURE 3 The simplified circuit of high-impedance grounding method. K_1: switch; T: grounding transformer; n: ratio of transformer; R, L: resistance and inductance of grounding instrument.

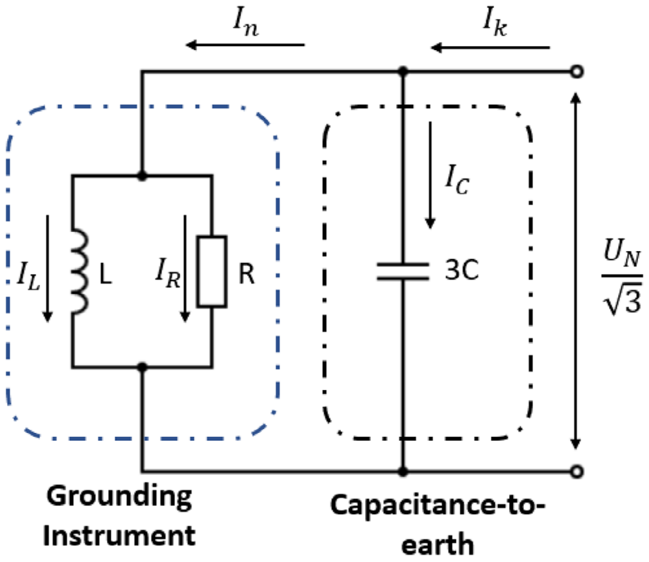


FIGURE 4 The equivalent circuit of high-impedance grounding method.

As Figure 4 shows, I_k is the single-phase earth fault current which is consisted by I_c (the capacitive currents are assumed to be identical), I_R resistive current, and I_L reactive current.

4.1 | Capacitive current

Capacitive current is normally from generator itself and the associated components, such as the main bus bar, plant transformer terminal bus bar, transformer secondary winding, shunt capacitors, and direct-fed load cables. This can be measured offline. The capacitive current is denoted as

$$I_c = \frac{U_N}{\sqrt{3}} * 3\omega C \tag{4}$$

where U_N is the rated voltage of the generator, C is the total capacitance.

4.2 | Neutral earth current

The neutral earth current I_n can be expressed as

$$\dot{I}_n = \frac{U_N}{\sqrt{3}n^2 R} - j\frac{U_N}{\sqrt{3}n^2 \omega L} \tag{5}$$

The resistive current part can be used to reduce the displacement voltage and the inductive current part can eliminate the capacitive current and single-phase earth fault current.

4.3 | Single-phase earth fault current

The generator portal current can be classified as resistive current and capacitive current. The resistive current is normally identical to the neutral resistive current. The capacitive current is the residual current after the compensation from the ground instrument.

$$I_k = \frac{U_N}{\sqrt{3}} * \sqrt{\left(\frac{1}{n^2 R}\right)^2 + \left(3\omega C - \frac{1}{\omega n^2 L}\right)^2} \tag{6}$$

4.4 | Displacement voltage and coefficient

The displacement voltage of the HIG method can be expressed as

$$\dot{U}_0 = -\frac{j\omega\left(C_A + \alpha^2 C_B + \alpha C_C\right)}{\left(\frac{3}{r_d} + \frac{1}{n^2 R}\right) + \left[j\omega\left(C_A + C_B + C_C\right) - j\frac{1}{\omega n^2 L}\right]}\dot{U}_A \tag{7}$$

The HIG method combines the advantages of both the ASG and HRG methods, which can either limit the arc overvoltage or reduce the single-phase earth fault current. The equation can be simplified as

$$U_0 = \frac{U_{bd}}{\sqrt{d^2 + v^2}} \tag{8}$$

where U_{bd} is neutral unbalanced voltage, $U_{bd} = -\frac{j\omega(C_A+\alpha^2 C_B+\alpha C_C)}{(\frac{3}{r_d})+j\omega(C_A+C_B+C_C)}\dot{U}_A$; v is off-tuning degree, $v = \frac{I_c - I_L}{I_c}$; d is damping factor, $d = \frac{I_R}{I_c}$.

According to the definition of DVC in Equation (1), the DVC can be expressed as

$$\mathrm{DVC} = \frac{U_0}{U_{bd}} = \frac{1}{\sqrt{d^2 + v^2}} = \frac{I_c}{I_k} \tag{9}$$

The coefficient depends on the off-tuning degree and damping factor, and the DVC can be calculated by I_c and I_k, and both current can be measured through experience. This coefficient can indicate the variance of neutral voltage impacted by inserting grounding instruments. Excessive neutral voltage can cause bad power quality, which then triggers the protection action. Therefore, DVC is an important indicator to measure the effectiveness of grounding instruments.

4.5 | Ratio of resistance to impedance

Although DVC can be used to measure the performance of the grounding method, it is still challenging to select optimal parameters for HIG. To achieve this, ratio of resistance to impedance is used. The ratio can effectively reflect the tolerance of arc overvoltage and single-phase earth fault current which is defined as

$$\mathrm{RoRI} = \frac{Z_R}{Z_{C-L}} = \frac{R\left(3n^2\omega^2 LC - 1\right)}{\omega L} \tag{10}$$

where RoRI stand for ratio of resistance to impedance which is defined as the ratio of the resistive component of the grounding transformer Z_R to the combined component Z_{C-L} which is composed by the capacitive component of the generator stator winding and inductive of the grounding transformer. A reasonable configuration of the impedance ratio takes into account both the arc overvoltage and the single-phase earth fault current, so that they meet the requirements at the same time.

The ratio can be used to deduce the optimal resistance and reactance as

$$R = \frac{\omega L \cdot \mathrm{RoRI}}{3n^2\omega^2 LC - 1} \tag{11}$$

4.5.1 | Optimal ratio of resistance to impedance

To obtain an optimal resistance and reactance, it is necessary to find an optimal RoRI first and it can be determined by the boundaries of single-phase-to-earth multiple and temporary overvoltage multiple. Conventionally, single-phase-to-earth multiple is normally used to assess performance of HRG instruments [12]. Higher multiple represents the grounding instrument is easier to produce high single phase to earth fault current. The single-phase-to-earth multiple in high impedance can be expressed as $\frac{I_k}{I_C - I_L}$. According to Equations (4)–(6), the

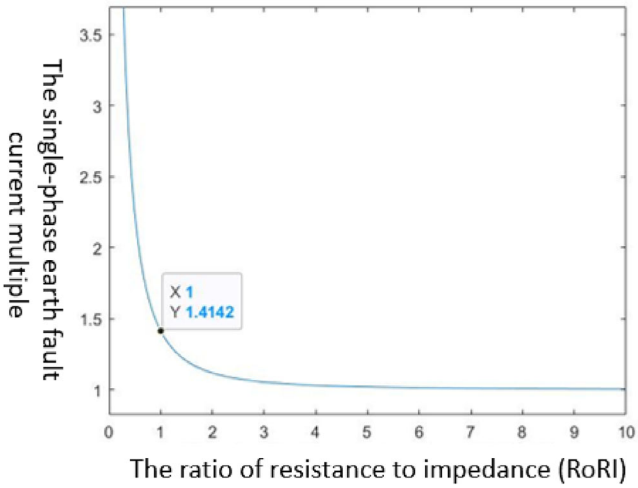


FIGURE 5 The relation between RoRI and single-phase earth fault current multiple. RoRI, the ratio of resistance to inductance.

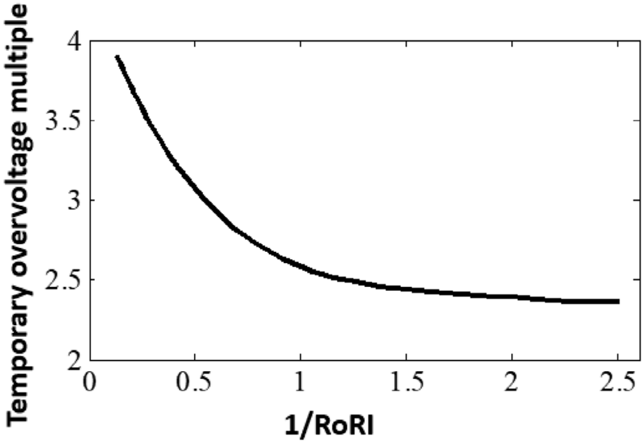


FIGURE 6 The relation between RoRI and temporary overvoltage multiple. RoRI, the ratio of resistance to inductance.

single-phase-to-earth multiple can be given as

$$\frac{I_k}{I_C - I_L} = \sqrt{1 + \left(\frac{1}{\mathrm{RoRI}}\right)^2} \tag{12}$$

According to Equation (12), single-phase-to-earth multiple only depends on the RoRI. Therefore, the relation of them can be given in Figure 5.

As Figure 5 shows, as RoRI increases, single-phase earth fault current multiple will approach 1 asymptotically, but once RoRI exceeds 2, achieving further increases will become signifncantly expensive. Considering both cost and performance of the HIG instrument, RoRI is expected to be from 1 to 2.

In addition to the single-phase-to-earth fault current, arc overvoltage is also critical for the parameter selection. According to [13, 14], the relation between arc overvoltage and the ratio of resistance to impedance is given in Figure 6.

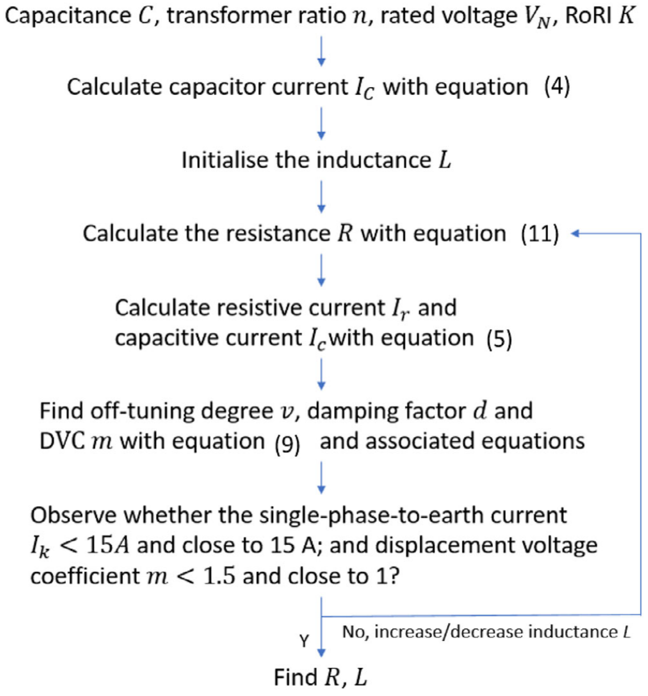


FIGURE 7 End-to-end process for optimal high-impedance grounding instruments selection.

Accordingly, the temporary overvoltage multiple is required to be greater than 2.6 [14]. Therefore, the RoRI should be less than approximately 1.2. Considering the limitation of both single-phase-to-earth multiple and temporary overvoltage multiple, the RoRI is recommended to use 1.2.

5 | PARAMETER SELECTION OF HIGH-IMPEDANCE GROUNDING METHOD

The last section has discussed the critical parameters of the HIG method. This section will further introduce the end-to-end process of the optimal parameters selection.

As shown in Figure 7, it is necessary to measure/collect the capacitive current with the provided capacitance, transformer ratio, rated voltage, and the ratio of resistance to inductance (RoRI). Then, the resistance can be obtained with an initial assumption of the inductance value. Following Equations (4) and (6), the single-phase-to-ground fault current and DVCs can be calculated. This process can be repeated until the optimal resistance and inductance values are achieved, which make the single-phase to earth fault current close to the required limit of 15 A and the DVC close to the required value of 1 (the DVC must be less than 1.5) according to the standard [15].

6 | CASE STUDIES

To test the effectiveness of the proposed high-impedance neutral grounding method in solving the problems of excessive

TABLE 1 The basic parameters of hydroelectric generator.

Parameters	Value
Rated voltage (kV)	13.8
Single-phase-to earth capacitance $C_A/C_B/C_C$ (μF)	2.281
RoRI	1.2
Transformer ratio	34.5
Capacitance current (A)	17.12

Abbreviation: RoRI, the ratio of resistance to inductance.

TABLE 2 Inductance and resistance selection via optimizing single-phase earth fault current and displacement voltage coefficient.

Inductance (mH)	Resistance (Ω)	Single-phase earth fault current (A)	Displacement voltage coefficient
3.5	0.73	14.36	1.19
3.6	0.72	14.58	1.17
3.7	**0.71**	**14.79**	**1.16**
3.8	0.70	14.98	1.14
3.9	0.69	15.17	1.13

The calculation does not consider the internal resistance of earth transformer.

neutral displacement voltage and excessive single-phase to earth fault current caused by increasing capacity for large/medium-sized hydroelectric generators, field tests and theoretical analyses have been conducted. A total of four SF175-68/1280 generators were used for the field tests, and their parameters were also used for the theoretical analyses. The rated capacity is 175 MW, and the stator voltage is 13.8 kV. The transformer model is SFP-24000/220 with a rated capacity of 240 MVA and a rated voltage of 220 kV. The earth connection is YN/D11. The rated capacity of the grounding transformer is 100 kVA, and the rated voltage is 13.8 kV/0.4 kV with a ratio of 34.5. Additionally, the key parameters of the generators are provided in Table 1.

6.1 | Instrument parameter design

Parameter selection of the proposed neutral ground method could affect its effectiveness. This section would show how to optimize parameters for the proposed high-impedance method and it uses the parameters in Table 1 for the calculation.

According to the process outlined in Figure 7, a selection of critical results for combinations of inductance and resistance values is presented in Table 2. In accordance with the standards [15, 16], the single-phase-to-ground fault current cannot exceed 15 A, and the DVC should be as close to 1 as possible. Therefore, to accommodate potential errors in the current calculations and satisfy both voltage and current requirements simultaneously, an inductance of 3.7 mH and a resistance of 0.71 Ω are selected to assemble the neutral grounding instrument for this generator.

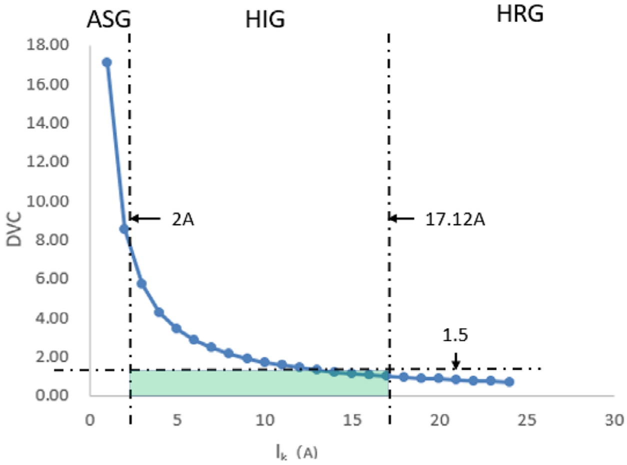


FIGURE 8 Relation between displacement voltage coefficient and single-phase earth fault current.

6.2 | Theoretical analysis

This section would use the process discussed in Section 5 to evaluate the proposed HIG instrument against the two conventional methods.

6.2.1 | Application of high-impedance grounding

According to Equation (9), the relationship between the DVC and the single-phase to earth fault current is negatively correlated for all grounding methods. Figure 8 has demonstrated this relationship for the SF175-68/1280 generator when the capacitive current is 17.12 A, as given in Table 1. Generally, the DVC should not exceed 1.5 according to [16]. As shown in Figure 8, its corresponding single-phase to earth fault current should be greater than 11 A for this generator. However, an excessively large single-phase to earth fault current would damage the generator's stator core, and the single-phase to earth fault current is required to not exceed 15 A; otherwise, the generator will be disconnected by the protection system. According to [14], ASG cannot exceed 2 A for an extended period due to safety concerns, and HRG will struggle with high single-phase to earth fault currents because it does not have an inductive component to reduce the capacitive current. Large-capacity hydroelectric generators typically have an unacceptably high capacitive current, such as 17.12 A for the generator used for testing here. This results in ASG and HRG being difficult to meet all the requirements of hydroelectric generators. The proposed HIG can satisfy these requirements, as highlighted in the shaded area of Figure 8, because it has both resistive and inductive components to reduce the single-phase-to-earth fault current and the DVC.

6.2.2 | Performance comparison

As discussed in Section 3, the single-phase to earth fault current and the DVC are two critical indicators to determine whether

TABLE 3 Performance comparison among different neutral grounding methods.

Method	Single-phase earth fault current (A)	Displacement voltage coefficient
ASG	2.00	4.79
HRG	24.12	0.71
High-impedance method	14.79	1.16
Threshold	<15	<1.5 and close to 1

Abbreviations: ASG, arc suppression grounding; HRG, high-resistance grounding.

a neutral grounding method is valid for a generator. According to the calculations following Figure 7, the single-phase to earth fault current and DVC of different grounding methods for the same 13.8 kV hydroelectric generator are calculated and presented in Table 3. For the 13.8-kV generator, according to the Chinese standard [14], the long-time allowable value for the single-phase grounding current is 2 A for ASG. The DVC is calculated using a 2-A single-phase-to-ground fault current and a 3% damping rate; the HRG method is calculated with the traditional design RoRI of 1; the HIG method is designed with the typical RoRI value of 1.2, as recommended in this paper. The single-phase-to-ground fault current is limited to 15 A [15], and the DVC is limited to 1.5 [16], as recommended in this paper.

As shown in Table 3, the DVC is reduced from 4.79 to 1.16 in the high-impedance method compared to ASG, representing a significant reduction. Compared to HRG, the single-phase to earth fault current of the proposed method can be reduced by 9.33 A. Although the single-phase to earth fault current is smaller under ASG, the DVC exceeds the upper limit; although the DVC is smaller under HRG, the single-phase-to-ground fault current exceeds the required limit. Only the proposed HIG method can meet both requirements simultaneously through reasonable selection of parameters.

6.3 | Field test

The high-impedance method is proposed for the first time, and there are no established standards for parameter limitations. Therefore, this paper utilized the closest grounding method (high-resistance method) to limit the grounding instrument's parameters. According to the requirements for HRG systems, the single-phase to earth fault current cannot exceed 15 A [15], the DVC should be less than 1.5 [16], and the arc overvoltage cannot exceed 2.6 times the rated phase-to-ground voltage. This paper installed the designed HIG instruments for four generators, where only the #1 generator's parameters were optimized following the process outlined in Section 5, and tested the instruments under no-load operation conditions.

Additionally, this paper has measured unbalanced voltage, displacement voltage, capacitive current, and single-phase-to-ground fault current for all the generators. The unbalanced voltage is measured without any grounding instrument and load; the displacement voltage is measured with a grounding instrument but without any load; the capacitive current is measured at the generator's export terminal without installing any grounding instrument and load when the generator is grounded, and the measured current needs to be scaled up to the value at rated voltage; the single-phase to earth fault current is measured with the grounding instrument but without any loads. Then, the measurements are used to further calculate the DVC. The parameters of four generators and their grounding instruments are given in Table 4.

As shown in Table 4, the single-phase-to-ground fault currents are all less than the short-time grounding current upper limit of 15 A, and the DVCs are all less than 1.5 [15, 16]. Additionally, the displacement voltage of #1 generator is significantly lower than the rest due to the proposed optimization method.

Compared with Table 2, due to the consideration of different capacitance currents of the generators and the internal impedance of the grounding transformers, there are differences between the calculated and measured values of the secondary resistance and secondary inductance of the neutral grounding devices for each generator. However, the difference between the displacement voltage and single-phase-to-ground fault current of the test results is acceptable, with a maximum difference of 27% in the DVC and 28% in the single-phase to earth fault current.

6.3.1 | Performance comparison

The most important indicators for evaluating a generator's neutral grounding method are the single-phase to earth fault current and the DVC. This section will compare and analyse three different grounding methods using #1 generator, and the measurements are shown in Table 5. The result of Table 5 is consistent with the theoretical calculation result in Table 2, and only the proposed high-impedance method can satisfy the requirements for both the single-phase-to-ground fault current and the DVC.

6.3.2 | Error discussion

Since the secondary resistance and secondary reactance change after considering the internal impedance of the grounding transformer in the design of the HIG device, a comparative analysis is required to determine the impact of the grounding transformer's internal impedance on the single-phase-to-ground fault current and displacement voltage. The comparative results of the parameters for the #1 generator's neutral grounding system are shown in Table 6. As can be seen from Table 6, the theoretical and measured values of each parameter are relatively close. The error for the secondary resistance is 2.7%, the error for the secondary inductance is 1.4%, the error for the single-phase-to-ground fault current is 4.6%, and the error for the DVC is 7.5%, indicating that the design method for the HIG is accurate.

TABLE 4 Error between theoretical analysis and field test.

Generator index	Unbalanced voltage (V)	Capacitance current (a)	Neutral secondary resistance (Ω)	Neutral secondary inductance (mH)	Displacement voltage (V)	Displacement voltage coefficient	Neutral current (A)	Single-phase earth fault current (A)
#4	476.00	16.69	0.76	2.02	672.90	1.41	20.6	13.13
#3	483.71	17.12	0.65	2.42	646.70	1.34	12.37	12.39
#2	478.72	16.32	0.64	2.39	657.12	1.37	11.97	10.79
#1	477.00	15.50	0.70	4.96	529.13	1.11	9.89	13.82

Unbalanced voltage can be measured when generator runs without grounding device and under no-load operation.
If a generator runs with grounding device but no load, the displacement voltage can be obtained.
If a generator is single-phase grounded at the terminals without grounding device and load, a single-phase to ground capacitance current can be obtained.
If a generator is single-phase grounded at the terminals with grounding device but without load, single-phase grounding current can be obtained.

TABLE 5 Field test of different ground methods.

Method	Unbalanced voltage (V)	Capacitance current (A)	Displacement voltage (V)	Displacement voltage coefficient
ASG	478.72	/	>1104[a]	>2.31[a]
HRG	478.72	23.00	345.4	0.72
High-impedance method	478.72	10.79	657.12	1.37

Abbreviations: ASG, arc suppression grounding; HRG, high-resistance grounding.
[a] Displacement voltage and displacement voltage coefficients cannot be directly measured, so the values are inferred by some trip events.

TABLE 6 Error between theoretical analysis and field test.

	Secondary resistance(Ω)	Secondary reactance(mH)	Single-phase earth fault current (A)	Displacement voltage coefficient
Theoretical[a]	0.72	4.89	14.50	1.07
Measure[b]	0.70	4.96	13.82	1.15
Relative error	2.7%	−1.4%	4.6%	−7.5%

[a] Theoretical is the value calculated with theoretical equations.
[b] Measure is the value measured from field test.

7 | CONCLUSION

A new HIG method for hydroelectric generators is proposed in this paper, which overcomes the shortcomings of high neutral displacement voltages under the ASG method and excessive single-phase-to-ground fault currents under the HRG method. The parameters of the HIG device can be designed using the proposed optimization method described herein. The design results can fully account for all constraints of hydroelectric generators, including limiting the neutral DVC less than 1.5 and the single-phase-to-ground fault current to less than 15 A, effectively solving the problems of excessive neutral displacement voltages and excessive single-phase-to-ground fault currents in medium and large hydroelectric generators. Additionally, this paper proposes a novel metric, the DVC, to measure the performance of neutral grounding methods in terms of voltage limitation, which is applicable to generators of different capacities. Currently, the application of the HIG method has been gradually adopted in large and medium-sized hydroelectric generators, significantly improving the security of these generators.

AUTHOR CONTRIBUTIONS

Jianming Jiang: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; validation; writing—original draft; writing—review and editing. **Xu Jiang**: Validation; visualization; writing—original draft; writing—review and editing. **Gongyi Song**: Investigation; project administration; validation. **Song Tong**: Funding acquisition; investigation; project administration. **Yanhai Li**: Investigation; project administration; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Research data are not shared.

ORCID

Jianming Jiang https://orcid.org/0009-0009-5643-459X

REFERENCES

1. Ge, D.: Electrical Engineering And Design Manual (Electrical Primary Side Part). China Electric Power Press (1989)
2. Jaafari, K.A., Toliyat, H.A.: Performance analysis of synchronous generators under stator windings ground faults near the star point—Experimental verification. IEEE Trans. Energy Convers. 35(3), 1402–1410 (2020). https://doi.org/10.1109/TEC.2020.2980619
3. Wu, A.Y.: MV generator ground fault arcing power damage assessment. IEEE Trans. Ind. Appl. 54(1), 912–915 (2018). https://doi.org/10.1109/TIA.2017.2753173
4. Klingerman, N., Finney, D., Samineni, S., Fischer, N., Haas, D.: Understanding generator stator ground faults and their protection schemes. In: 2016 69th Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, USA, pp. 1–14 (2016). https://doi.org/10.1109/CPRE.2016.7914921
5. Jiang, J.: CSEE 0094–2019 The technical specification of generator neutral grounding transformer devices (2019)
6. Zhang, Q.X., Wang, X.H., Wang, W.J.: Transient analysis on large hydro-generator with high resistance grounding. Power Syst. Technol. 28(30–33), 37 (2004)
7. Yushi, C., Yishou, T.: The configuration method of using high-impedance distribution transformer to ground the neutral point of large generators. J. Yangtze River Sci. Res. Inst. 28(9), 68–70 (2011)
8. Klingerman, N., Finney, D., Samineni, S., Fischer, N., Haas, D.: Understanding generator stator ground faults and their protection schemes. In: 2016 69th Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, USA, pp. 1–14 (2016). https://doi.org/10.1109/CPRE.2016.7914921
9. Bais, M., Basit, A., Ali, S., Sadiq, M., Ahmad, I.: Design and analysis of neutral grounding transformer for hydro alternators. Int. J. Eng. Work. 06(10), 374–378 (2019)
10. 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 10(7), 554 (2022)
11. Tan, L., Wang, Y., Yin, X., Qiao, J., Xu, W.: Injected current regulation based stator ground fault arc suppression method for large hydro-generators. Int. J. Electr. Power Energy Syst. 143, 108513 (2022). https://doi.org/10.1016/j.ijepes.2022.108513
12. Bi, D., Wang, X., Wang, W.: Study on how to ground for the neutral point of large-sized hydro-generator. Trans. China Electrotech. 17(4), 7–12 (2002)
13. Wang, W., Gui, L., Wang, X., Sun, Y., Sheng, H., Li, H., Zhang, Q.: Reconsideration and anxiety of neutral grounding mode for large generator. Electr. Equip. 8(11), 1–4 (2007)
14. China Energy Aminidstration: NB/T 35067-2015 Overvoltage protection and insulation coordination design guide for hydropower Station (2015)
15. IEEE Guide for Generator Ground Protection. ANSI/IEEE C37.101-1985, pp. 1–43 (1985)
16. The technical specification of generator neutral grounding transformer devices. T/CSEE 10290002–2019 (2019)

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