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Abstract: In view of the difficulties in coordination between reliability and sensitivity of conventional generator differential protection, this paper presents a novel generator differential protection scheme based on a new braking method. On the basis of the mathematical model of the field-circuit coupling method and the electrical network cascade characteristics, the stator windings were combined and decoupled by the improved six-sequence component method to eliminate electromagnetic coupling between winding coils. In accordance with the basic characteristics of longitudinal impedance, the function of sub-item discrimination was realized. Numerous simulations and the up-to-date dynamic experiments showed that the proposed method has good state discrimination ability and can effectively resist the influence of current transformer saturation. Thus, it has an excellent prospect for engineering promotion.

Keywords: differential protection; generator protection; phase-to-phase fault; winding structure; longitudinal impedance

1. Introduction

Over the past few years, we have witnessed that large generators play an important role in the optimization and upgrading of power supply and grid structure. On one hand, new energy power generation has been developed on a large scale in China. The proportion of new energy power generation installed capacity exceeded 50% for the first time in 2017, and the intermittent and randomness of its output brings challenges to the stability of the power system [1,2]. On the other hand, the wide application of new power electronic technologies, such as large-scale DC transmission and flexible AC/DC transmission, makes the operating characteristics of the power system more complex and changeable [3,4]. As the main power source of the power system, large generators can not only cope with the complex operating environment of the power grid, but also provide stronger support for the power grid.

In the case of the characteristics of high operating efficiency and low pollution, large generators' installed capacity has increased steadily. Its design, structure, technology, operation, etc. have become more complicated, and higher requirements have been put forward for its protection configuration [5]. In fact, traditional differential protection has the defect that it is hard to coordinate between anti-misoperation and non-rejection. Thus, an in-depth investigation of the change rule of each electrical quantity after an internal fault, which occurs in the generator, is conducive to the research of new generator protection algorithms and further improves the effectiveness of generator operation.

In the system, the stator internal short circuit is a kind of common fault that may compromise the security of the generator. Relevant scholars have done a lot of research on the



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). protection types of it [6–8]. In general, generator differential protection is the main protection for large-scale power station generators and generator transformers. Pillai P. et al. [9] analyzes and discusses the choice of neutral grounding method and makes a detailed comparison of the influence of high-resistance grounding method and arc suppression coil grounding method in differential protection. Chen, X. et al. [10] shows that, although large units used separated-phase enclosed bus generally, it is still necessary to consider the possibility of phase-to-phase short-circuit faults in the generator voltage circuit. So. the protection areas of generator differential protection and transformer differential protection should overlap each other. Shipp D. et al. [11] shows that if the stator winding of the synchronous generator is short-circuited between the upper and lower bars of the same slot and the end of the coil, it will cause great harm to the motor. When an internal fault occurs, the short-circuit current increases sharply, which not only produces destructive electromagnetic forces but also overheats and burns the windings and iron cores. Therefore, the protection must act immediately to prevent serious damage to the generator. Safari-Shad N. et al. [12,13] adopts full longitudinal differential protection and incomplete longitudinal differential protection, which can remove faulty components from the power system selectively. However, it can be seen that the fault analysis mainly stays on the short-circuit level of the terminal of the protected equipment. The corresponding main equipment protection sensitivity analyses' calculation is also limited to the verification of the short circuit of the terminal. So, even if the sensitivity coefficient verification is qualified, when the internal failure of the protected equipment occurs, it is difficult to ensure that the protection device is sensitive and quick to operate. Therefore, from the perspective of unit protection, it is necessary to analyze the distribution qualitatively and quantitatively and change laws of various electrical quantities during internal faults to design the configuration scheme of internal fault protection, so as to achieve the purpose of reducing fault damage. Zhu, Y. et al. [14] shows that rotor second harmonic current protection can reflect the abnormal operating conditions of electrical components but has higher requirements for the reliability and performance of the signal source. Jaafari K. et al. [15] makes the use of the scalar product braking longitudinal differential protection, which has defects in setting calculation and principles' design. Gao, B. et al. [16] uses transverse differential protection, which has a simple principle and high sensitivity, but it has no protective effect on the short circuit of the external lead of the machine end and the on-site debugging is more complicated. Zheng, T. et al. [17] utilizes fundamental longitudinal zero-sequence voltage protection, but its protection action has a low correct rate and there are some areas that cannot be protected. Xia, J. et al. [18,19] proposes to solve the problems caused by the saturation of conventional current transformers and to ensure the accuracy of the collected current sampling values or phasors in order to avoid protection malfunctions. Therefore, researching a new braking method for generator differential protection is beneficial to the safe operation of the power system.

Firstly, in view of the problems of traditional differential protection in generator protection, this research made use of the field-circuit combination method [20] and took the influence of the mutual inductance of the generator's internal windings into consideration to build a more complete, large-scale, turbo-generator model and to reduce complexity and improve accuracy.

Secondly, on the basis of the calculation method for the longitudinal impedance of transmission line at both ends [21], an improved algorithm suitable for generator differential protection was proposed. This algorithm retained the operating characteristics of the current longitudinal differential protection, combined the characteristics of the generator stator windings, and utilized the differential current of the fault component to enhance the robustness of the algorithm. The ratio of the voltage fault component difference at both ends to the positive sequence series impedance of the winding was used as the braking amount of protection and the reliability of the improved algorithm was further improved. By improving the decoupling of the six-sequence component method, the improved algorithm component method component method, the improved algorithm component method component component component method, the improved algorithm component component method, the improved algorithm component component component component component component method, the improved algorithm component c

rithm was constructed in this paper to reduce the influence of the stator winding phase coupling on the protection and realize its sub-state recognition function.

2. Improved Decoupling Method of Generator Stator Winding

The classical generator short-circuit fault calculation methods are mainly the symmetrical component methods [22,23]. However, when the internal generator fault happens, the sequence components are interdependent. The DC component, the fundamental frequency component, and double frequency component in the stator and rotor will affect the change characteristics of the electrical quantity. In this case, in the light of the superposition principle, the symmetrical component method is not suitable for the internal fault analysis for large generators. When a short-circuit fault occurs in the winding, the mutual inductance not only exists between phases, but also loops. So, the six-sequence component analysis method can be used for this case [24,25]. For the three-phase, double-layer winding, the conductors of each layer are divided into upper and lower layers. The coil is composed of the upper conductor in one slot and the lower conductor in the other, making the stator winding parameters of the same slot asymmetrical. This causes a deviation between the results obtained by the six-sequence component method and the actual results, and then the sequence component decomposition method must be adjusted.

Referring to the stator windings, this research used the improved six-sequence component method for decoupling [26,27]. Firstly, the current was decomposed into positive sequence, negative sequence, and zero sequence. Then, the zero sequence was decomposed into zero-sequence identical direction vectors and zero-sequence reverse direction vectors, while the positive sequence and negative sequence remained unchanged.

As shown in Figure 1, the parameters of the stator winding loop I and II at the same slots were different, but the internal parameters of each loop were symmetric. Z_{s1} was the self-inductance of the winding stator winding I loop, and Z_{m1} was the mutual inductance between phases, Z_{s2} was the self-inductance of the stator winding of loop II, Z_{m2} was the mutual inductance between phases, and Z_p was the mutual inductance between two stator winding loops in the same slot. The voltage–current relationship between the stator windings can be written in a vector matrix, as in Equation (1).



Figure 1. Coupling circuit diagram.

$$\begin{bmatrix} \Delta U_{IA} \\ \Delta \dot{U}_{IB} \\ \Delta \dot{U}_{IC} \\ \Delta \dot{U}_{IIA} \\ \Delta \dot{U}_{IIB} \\ \Delta \dot{U}_{IIC} \end{bmatrix} = \begin{bmatrix} Z_{s1} & Z_{m1} & Z_{m1} & Z_{p} & Z_{p} & Z_{p} \\ Z_{m1} & Z_{s1} & Z_{m1} & Z_{p} & Z_{p} & Z_{p} \\ Z_{p} & Z_{p} & Z_{p} & Z_{p} & Z_{p} & Z_{m2} \\ Z_{p} & Z_{p} & Z_{p} & Z_{m2} & Z_{s2} & Z_{m2} \\ Z_{p} & Z_{p} & Z_{p} & Z_{m2} & Z_{m2} & Z_{s2} \end{bmatrix} \begin{bmatrix} I_{IA} \\ \dot{I}_{IB} \\ \dot{I}_{IC} \\ \dot{I}_{IIA} \\ \dot{I}_{IB} \\ \dot{I}_{IC} \end{bmatrix}$$
(1)

where ΔU_{IA} , ΔU_{IIA} , ΔU_{IB} , ΔU_{IIB} , ΔU_{IC} , ΔU_{IIC} are, respectively, the voltage drops across winding stator winding.

By using the symmetrical component method, Equation (1) can be decomposed into positive sequence, negative sequence, and zero sequence, as in Equation (2).

$$\begin{array}{c} \Delta U_{10} \\ \Delta \dot{U}_{11} \\ \Delta \dot{U}_{12} \\ \Delta \dot{U}_{10} \\ \Delta \dot{U}_{I11} \\ \Delta \dot{U}_{I12} \end{array} \right] = \begin{bmatrix} Z_{I0} & 3Z_p & & \\ & Z_{I1} & & & \\ & & Z_{I2} & & \\ & & Z_{I2} & & \\ & & & Z_{I10} & & \\ & & & & Z_{I11} & \\ & & & & & Z_{I12} \end{bmatrix} \begin{bmatrix} I_{10} \\ \dot{I}_{11} \\ \dot{I}_{12} \\ \dot{I}_{10} \\ \dot{I}_{111} \\ \dot{I}_{12} \end{bmatrix}$$
(2)

In Equation (2), the subscript I represents loop I, II represents loop II, 0 represents zero sequence, 1 represents positive sequence, and 2 represents negative sequence.

It can be obtained from Equation (2) that there is no coupling between the positive sequence and the negative sequence of the two loops for the winding stator winding after transformation and only the zero sequence of the two loops is coupled. Therefore, it is only necessary to decouple the zero-sequence mutual inductance between the lines. So, it is going to extract the zero-sequence component in Equation (2), as in Equation (3).

$$\begin{array}{c} \Delta \dot{U}_{\rm I0} \\ \Delta \dot{U}_{\rm II0} \end{array} \right] = \left[\begin{array}{cc} Z_{\rm I0} & 3Z_p \\ 3Z_p & Z_{\rm II0} \end{array} \right] \left[\begin{array}{c} \dot{I}_{\rm I0} \\ \dot{I}_{\rm II0} \end{array} \right]$$
(3)

Equation (3) is equivalent, as in Equation (4).

$$\mathbf{D}\hat{U}_0 = Z_0\hat{I}_0 \tag{4}$$

By decoupling the zero-sequence mutual inductance, diagonalizing Z_0 , where Z_0 $\begin{bmatrix} Z_{I0} & 3Z_p \\ 3Z_p & Z_{II0} \end{bmatrix}, \text{ and recording the diagonalized change matrix as } \prod = \begin{bmatrix} 1 & 1 \\ \gamma_1 & \gamma_2 \end{bmatrix}, \text{ includ-}$ $\text{ing } \gamma_1 = \frac{Z_{II0} - Z_{I0} + \sqrt{(Z_{II0} - Z_{I0})^2 + 36Z_p^2}}{6Z_p}, \gamma_2 = \frac{Z_{II0} - Z_{I0} - \sqrt{(Z_{II0} - Z_{I0})^2 + 36Z_p^2}}{6Z_n}.$

Perform \prod transformation on Equation (4), as in Equation (5

$$\Delta \dot{U}_{0}^{\prime} = \prod^{-1} Z_{0} \prod \dot{I}_{0}^{\prime}$$
(5)

to write in matrix form after equivalent, as in Equation (6):

$$\begin{bmatrix} \Delta \dot{U}_{10} \\ \Delta \dot{U}_{20} \end{bmatrix} = \begin{bmatrix} Z_{10} & \\ & Z_{20} \end{bmatrix} \begin{bmatrix} \dot{I}_{10} \\ & \dot{I}_{20} \end{bmatrix}$$
(6)

where ΔU_{10} and I_{10} are the first components of the zero-sequence voltage and current after decoupling; ΔU_{20} and I_{20} are the second components of the zero-sequence voltage and current after decoupling; Z_{10} is the impedance corresponding to the first component of the zero sequence, i.e., $Z_{10} = \frac{1}{2} \left[Z_{I0} + Z_{II0} + \sqrt{(Z_{I0} - Z_{II0})^2 + 36Z_p^2} \right]$; and Z_{20} is the impedance corresponding to the second component of the zero sequence, i.e., $Z_{20} = \frac{1}{2} \left[Z_{I0} + Z_{II0} - \sqrt{(Z_{I0} - Z_{II0})^2 + 36Z_p^2} \right]$.

Combine Equation (3) and Equation (6), as in Equation (7).

$$\begin{bmatrix} \Delta U_{10} \\ \Delta U_{11} \\ \Delta U_{12} \\ \Delta U_{20} \\ \Delta U_{21} \\ \Delta U_{22} \end{bmatrix} = \begin{bmatrix} Z_{10} & & & & \\ & Z_{11} & & & & \\ & & Z_{12} & & & \\ & & & Z_{20} & & \\ & & & & Z_{21} & & \\ & & & & & Z_{22} \end{bmatrix} \begin{bmatrix} I_{10} \\ I_{11} \\ I_{12} \\ I_{20} \\ I_{21} \\ I_{22} \end{bmatrix}$$
(7)

From Equation (7), the impedance matrix can be obtained as a diagonal matrix, the decoupling between the double-circuit stator winding of the generator stator winding has been completed, and the influence of the phase coupling of the stator winding can be eliminated after decoupling.

3. Improved Algorithm of Generator Differential Protection

Figure 2a,b shows the R-L (Resistive Load) single-phase stator winding equivalent power frequency fault component models when the external and internal faults of the generator stator windings occur, respectively [28]. The theoretical analysis ignores the influence of the ground capacitance.



Figure 2. Equivalent circuit model when the generator fails. (a) External fault; (b) internal fault.

In Figure 2, ΔU_l , ΔU_r , ΔI_l , and ΔI_r are the voltage fault components and current fault components obtained on the *l* side and *r* side, respectively; Z_{ls} and Z_{rs} are the equivalent system impedances at the *l* side and *r* side; Z_m is the excitation impedance; Z_l and Z_r are the equivalent leakage impedance inside the generator, respectively; I_m is the excitation current; and the reference direction is from the bus bar to the generator.

3.1. Ratio Braking Differential Protection

In view of the differential protection with traditional ratio braking characteristics, we can get:

$$\begin{cases} \dot{I}_{op} = \left| \Delta \dot{I}_l + \Delta \dot{I}_r \right| \\ \dot{I}_{res} = \frac{1}{2} \left| \Delta \dot{I}_l - \Delta \dot{I}_r \right| \end{cases}$$
(8)

Its action criterion is as in Equation (9).

$$\begin{cases} \left| \dot{I}_{op} \right| \ge \left| \dot{I}_{act.min} \right| & \dot{I}_{res} \le \dot{I}_{res.min} \\ \left| \dot{I}_{op} - \frac{1}{2} \left(\dot{I}_{res} - \dot{I}_{res.min} \right) \right| \ge \left| \dot{I}_{act.min} \right| & \dot{I}_{res} \le \dot{I}_{res.min} \end{cases}$$
(9)

where I_{op} is the differential current, I_{res} is the braking current, $I_{act.min}$ is the minimum operating current, and $I_{res.min}$ is the minimum braking current.

3.2. Differential Protection Algorithm Based on Longitudinal Impedance

3.2.1. External Fault

As shown in Figure 2a, if an external fault occurs at the side of the generator, U_F is the voltage at the fault point, I_F is the current at the fault point, and Z_{r1s} , Z_{r2s} are the two equivalent impedances separated after an external fault. When the generator is operating normally or an external fault occurs, we can get: $|Z_m| \gg |Z_r + Z_{rs}|$. If the influence of shunt current caused by Z_m is not considered, the deductions can be obtained as in Equations (10) and (11).

$$\begin{cases} \Delta \dot{U}_l = -\Delta \dot{I}_l Z_{ls} \\ \Delta \dot{U}_r = \dot{U}_F - \Delta \dot{I}_r Z_{r2s} = \Delta \dot{U}_l + \Delta \dot{I}_r (Z_l + Z_r) \end{cases}$$
(10)

$$\begin{cases} \Delta \dot{U}_{op} = \Delta \dot{I}_l (Z_l + Z_r) = -\Delta \dot{I}_r (Z_l + Z_r) \\ \Delta \dot{I}_{op} = \Delta \dot{I}_l - (-\Delta \dot{I}_r) = \Delta \dot{I}_l + \Delta \dot{I}_r \end{cases}$$
(11)

Based on the fault network shown in Figure 2, the longitudinal impedance expresses as in Equation (12).

$$\Delta Z_{op} = \left| \frac{\Delta \dot{U}_{op}}{\Delta \dot{I}_{op}} \right| \tag{12}$$

From the internal structure of the generator, the positive sequence stator winding impedance of the winding does not need to be adjusted and reset in accordance with the changes of the system operation mode. Therefore, in the ideal state, the amplitude of $\Delta \dot{I}_l$ and $\Delta \dot{I}_r$ is basically the same and there exists $\left|\Delta \dot{I}_{op}\right| = \left|\Delta \dot{I}_l + \Delta \dot{I}_r\right| = 0$, i.e., $\left|\Delta \dot{I}_l\right| >> \left|\Delta \dot{I}_{op}\right|$. Equation (12) can be transferred to obtain an improved algorithm of the current differential protection form expressed, as in Equation (13).

$$\left|\Delta \dot{I}_{l} + \Delta \dot{I}_{r}\right| < \left|\frac{\Delta \dot{U}_{l} - \Delta \dot{U}_{r}}{Z_{op}}\right| \tag{13}$$

According to the above derivation, for external faults, the amount of action is obviously smaller than the braking amount, which ensures the reliability of the improved algorithm.

3.2.2. Internal Fault

As shown in Figure 2b, for internal fault at the *r* side of the generator, U_F is the voltage at the fault point, I_F is the current at the fault point, and Z_{r1} and Z_{r2} are two equivalent leakage impedances separated at the internal fault. When the generator is at normal operation, we can get $|Z_m| \gg |Z_{r1} + Z_{r2} + Z_{rs}|$. If the influence of shunt current caused by Z_m is not considered, the deductions can be obtained as in Equations (14) and (15).

$$\begin{cases} \Delta \dot{U}_l = -\Delta \dot{I}_l Z_{ls} = \dot{U}_F - \Delta \dot{I}_l (Z_l + Z_{r2}) \\ \Delta \dot{U}_r = \dot{U}_F - \Delta \dot{I}_r Z_{r1} = -\Delta \dot{I}_r Z_{rs} \end{cases}$$
(14)

$$\begin{cases} \Delta \dot{U}_{op} = \Delta \dot{I}_l (Z_l + Z_r) - \Delta \dot{I}_r Z_{r1} \\ \Delta \dot{I}_{op} = \Delta \dot{I}_l + \Delta \dot{I}_r \end{cases}$$
(15)

In Equation (15), the direction of ΔI_l and ΔI_r is the same as the direction of the reference current, and from $\Delta \dot{I}_{op} = \Delta \dot{I}_l + \Delta \dot{I}_r$, we can get: $\Delta \dot{I}_l \leq \Delta \dot{I}_{op}$ and $\Delta \dot{I}_r \leq \Delta \dot{I}_{op}$. Equation (15) can be transformed into an improved algorithm of the current differential protection form expressed, as in Equation (16).

$$\left|\Delta \dot{I}_{l} + \Delta \dot{I}_{r}\right| > \left|\frac{\Delta \dot{U}_{l} - \Delta \dot{U}_{r}}{Z_{op}}\right|$$
(16)

According to the above derivation, for internal faults of the generator, the action volume is significantly greater than the braking volume, which ensures the sensitivity of the improved algorithm for internal faults.

3.2.3. Generator Differential Protection Algorithm Based on Longitudinal Impedance

From the above analyses, the discriminant of the new type of protection can be obtained as in Equation (17).

$$\left|\Delta \dot{I}_{l} + \Delta \dot{I}_{r}\right| - \left|\frac{\Delta \dot{U}_{l} - \Delta \dot{U}_{r}}{Z_{op}}\right| > I_{set}$$
(17)

When an external fault occurs on the generator, the amount of action is significantly smaller than the braking amount, the above Equation (17) is not established, and the protection is reliable and does not operate. When an internal fault occurs on the generator, the amount of action is obviously greater than the amount of braking, the above Equation (17) is established, and the protection is sensitive.

3.3. The Effect of Transition Resistance under Transient Conditions

The last section analyzes the differential protection method from the principle of using the steady-state transition resistance. This section considers the influence of the state of capacitance or inductance under transient conditions and makes corresponding analyses. Figure 3 is the simplified equivalent circuit.



Figure 3. Simplified equivalent circuit model of generator.

As shown in Figure 3, when a phase-to-phase short-circuit internal fault occurs in generator, the current expression at the fault point occurs, as shown in Equation (18).

$$\dot{I}_F = \frac{\dot{U}_F}{Z_F + Z_l \parallel Z_r} \tag{18}$$

where Z_F is the transient impedance and $Z_l \parallel Z_r$ is the parallel connection of the equivalent impedance on both sides of the fault point.

When the impedance Z_F is capacitive, the value of I_F is larger than when it is resistive, and the protection is more sensitive. When the impedance Z_F is inductive, the setting value I_{set} is set according to the maximum unbalanced current to avoid the external fault. If the inductance is large enough to affect the correct action of protection, the filtering effect can be strengthened and the discrimination time can be extended to protect.

4. Performance Analysis

Anti-Current Transformer Saturation Capability

When an external fault occurs in the stator winding of the generator, the short-circuit current near the fault side increases, it causes the current transformer near the fault side to saturate, the unbalanced current increases sharply, and there is a hidden danger of protection malfunction. This section combines the current transformer saturation law and the law of conservation of energy in the process of short-circuit current, taking an example of an external fault close to the fault side of a single-phase winding for analysis. The equivalent current waveform of the current transformer after transient saturation is shown in Figure 4. The figure, respectively, shows the primary-side current amplitude before saturation of the current transformer and the secondary-side current amplitude under the most severe transient saturation of the current transformer. The conduction angle θ is defined as the difference between the current zero-crossing point and the saturation point. The $\theta \sim \pi - \theta$ is the transient saturation of the current transformer.



Figure 4. Current waveform after transient saturation of current transformer.

The power frequency current component after the transient saturation of the current transformer can be expressed as in Equation (19).

$$I_{m0} = \int_{-\pi}^{\pi} \sin t \cdot \sin t dt = \sin \theta (\pi - 2\theta) - 2\cos \theta$$
(19)

It can be seen from Figure 4 that in the negative half waveform of the current, the excitation current is gradually demagnetized. At the same time, the excitation inductance gradually increases and the amplitude of the fundamental component of the current transformer current does not attenuate too much. In the positive half waveform of the current, the excitation current enters the saturation process from the operating point. When the transient saturation of the current transformer current attenuates as the degree of transient saturation increases. When the transient saturation of the current transformer saturation of the current transformer reaches π , the current transformer saturation is the most serious at this time. The qualitative reflection of the current decays to 50% of the original due to saturation. So, the transient current is half of the original current.

Substituting this conclusion into Equation (8) for analysis, the current amplitude is $\frac{1}{2}\Delta I_r$ and the phase is basically unchanged.

When the transient saturation angle of the current transformer is π , the action amount and braking amount of the traditional algorithm can be expressed as in Equation (20).

$$\begin{cases} \dot{I}_{op} = \left| \Delta \dot{I}_l + \Delta \dot{I}_r \right| = \Delta \dot{I}_l - \frac{1}{2} \Delta \dot{I}_r \\ \dot{I}_{res} = \frac{1}{2} \left(\Delta \dot{I}_l + \frac{1}{2} \Delta \dot{I}_r \right) = \frac{1}{2} \Delta \dot{I}_l + \frac{1}{4} \Delta \dot{I}_r \end{cases}$$

$$(20)$$

When an external fault occurs and the excitation current is ignored, it is $\Delta_l \approx \Delta I_r$. So, the discrimination margin of the differential protection is $K_{rel} = \frac{I_{set}}{I_{res.max}} = 1.5$. When the fault current transformer outside the area is saturated, its reliability coefficient is 1.5.

At the same time, when the transient saturation angle of the current transformer is π , the action amount and braking amount of the improved algorithm can be expressed as in Equation (21).

$$\begin{cases} \dot{I}_{op} = \left| \Delta \dot{I}_l + \Delta \dot{I}_r \right| = \Delta \dot{I}_l - \frac{1}{2} \Delta \dot{I}_r \\ \dot{I}_{res} = \left| \frac{\Delta \dot{U}_l - \Delta \dot{U}_r}{Z_{op}} \right| = \Delta \dot{I}_l + \frac{1}{2} \Delta \dot{I}_r \end{cases}$$
(21)

When an external fault occurs and the excitation current is ignored, it is $\Delta I_l \approx \Delta I_r$. The single-sided current transformer is most severely saturated. So $K_{rel} = \frac{\dot{I}_{set}}{\dot{I}_{res,max}} = 3$ shows that the reliability coefficient of this algorithm has a double margin at least. Therefore, the improved algorithm has a strong ability to resist transient saturation of current transformers in generator windings.

5. Simulation Verification

5.1. Digital Simulation

5.1.1. Simulation System and Its Parameters

Aiming at verifying the performance of the improved algorithm for generator differential protection proposed in this paper, the simulation software PSCAD (4.6.2, Manitoba HVDC Research Centre, Manitoba, Canada) was used to establish a stator winding simulation model of the stator winding and to simulate faults at different positions and different types.

The generator model is shown in Figure A1 in the Appendix A. In this figure, K_1 , K_2 , and K_3 are the external fault points; K_4 , K_5 , and K_6 are the internal fault points; the power supply and equivalent lines in the model are represented by the stator winding parameter model; and the specific parameters are as follows.

The rated capacity of the generator is 660 MW. The rated voltage is 20 kV. The rated power factor is 0.9. The rated frequency is 50 Hz. The number of stator slots is 18. The number of poles is two. Each phase resistance of the stator winding is $3.6 \text{ m}\Omega$. Each phase inductance of stator winding is 227.05μ H. The capacitance of each phase of the stator winding is 1.686μ F. The capacitance of the external connection equipment of the generator is 1.6μ F. The inductance of the arc suppression coil is 2.0032 H. The resistance of the neutral point of high resistance grounding is 629.32Ω .

5.1.2. Simulation Results and Analysis

The types of simulated faults are single-phase ground fault and two-phase short circuit. The simulation data in PSCAD software was imported into MATLAB software (R2013a, MathWorks, Natick, MA, USA), and the discrimination performance of the proposed improved protection algorithm was simulated and verified. The simulated waveforms are shown in Figure 5. The simulation results are shown in Tables 1–3. We took the 50% of the high-resistance internal ground faults at phase B and metallic ground external faults as examples (an internal fault is K_5 and an external fault is K_2).

When an internal occurs in the stator winding of the generator, the fault component current and voltage differences are shown in Figure 5. The comparison of braking current between traditional protection and new protection are shown in Figure 6. The comparison of the sensitivity of traditional protection and new protection are shown in Figure 7.

When an external occurs in the stator winding of the generator, the current sum and voltage difference of the fault component are shown in Figure 8. The comparison of braking current between traditional protection and new protection are shown in Figure 9. The transient saturation state of the current transformer under different residual magnetism conditions are shown in Figure 10.



Figure 5. High-resistance grounding fault at 50% of phase B. (**a**) Sum of fault component current. (**b**) The voltage difference of the fault component.

From Figure 6, it can be seen that when an internal fault occurs in the stator winding of the generator, the current sum at both ends of the winding stator winding is always greater

than the ratio of the voltage phasor difference to the line impedance and significantly greater than the set value and the protection is sensitive. It shows that the data are stable, the results are reliable, and the criterion structure is clear. When the reliability external is enhanced, the sensitivity of the traditional protection zone will be reduced. Considering capacitance, measurement deviation, transient effects, etc., there are amplitude errors and refusal to move. The protection braking current proposed in this paper is more stable than the traditional protection braking current, which increases the protection discrimination margin. The results are fully in line with the results of the abovementioned characteristic analysis and have the ability to further expand and develop.



Figure 6. Comparison of fault braking current between traditional protection and new protection. (**a**) Stability comparison. (**b**) Amplitude deviations.

From Figure 7, it can be seen that the action current of the proposed protection is twice greater than the braking current [24], which makes the protection have reliable action and higher sensitivity. Therefore, using the fault component longitudinal impedance amplitude criterion can identify the internal fault correctly and act on the trip directly without any latching, which is fast and reliable.



Figure 7. Comparison of sensitivity check. (a) Sensitivity check waveform of traditional protection. (b) Sensitivity check waveform of new protection.



11 of 16



Figure 8. External fault with metallic grounding in phase B. (**a**) Sum of fault component current. (**b**) The voltage difference of the fault component.

From Figure 9, it can be seen that when the generator is at normal operation or an external short circuit occurs, the sum of currents at both ends of the winding stator winding are less than the ratio of the voltage phasor difference to the winding impedance, which is significantly less than the set value, so the protection is reliable and does not operate. Therefore, the protection braking current of the proposed protection is smaller than the traditional one and makes the protection reliability higher.



Figure 9. Waveform diagram of fault action current when an external fault occurs on phase B with metallic grounding.



Figure 10. Current transformer saturation state.

It can be concluded from Figure 10 that the current transformer is in a state of transient saturation and its secondary-side current amplitude decreases relative to the primary-side

current amplitude. With the changes of the excitation parameters and the secondary-side current parameters, the transient saturation of the current transformer becomes serious and the difference between the phase of the current on the secondary side and its current amplitude are obvious.

The simulation results are shown in Tables 1 and 2, where I_{res} is the braking amount of the traditional protection algorithm in Equation (9) and K_{sen1} and K_{sen2} are the sensitivity of the traditional protection algorithm in Equation (8) and the sensitivity of Equation (11), respectively. (The sensitivity is defined as the ratio of the action amount to the braking amount.) Table 3 shows the simulation results of current transformer saturation for the external single-phase grounding fault at the generator outlet. In Table 3, "NO" means that the protection is not activated.

Table 1. Comparison of single-phase ground fault simulation results of two algorithms.

Fault Location	Fault Type	Transition Resistance/ Ω	Phase Sequence	I_r/A	I _{res} /A	I _{RES} /A	K _{sen1}	K _{sen2}
	Ag	0	А	103.0	3433.3	11,445.5	0.03	0.009
			В	17.3	76.2	3438.7	0.23	0.005
V			С	17.3	76.2	3438.7	0.23	0.005
ĸ ₁			А	18.4	223.1	816.5	0.08	0.023
	Ag	100	В	2.64	8.34	189.8	0.32	0.017
			С	2.64	8.34	189.8	0.32	0.017
		0	А	17.2	46.5	3416.4	0.37	0.005
	Cg		В	17.2	46.5	3416.4	0.37	0.005
V			С	105.5	1757.8	13,174.3	0.06	0.008
K3	Cg	100	А	5.39	12.9	215.8	0.42	0.025
			В	5.39	12.9	215.8	0.42	0.025
			С	17.2	24.2	1146.3	0.71	0.015
<i>K</i> ₅		0	А	11.6	17.4	2325.2	0.67	0.005
	Bg		В	66,672.2	13,254.9	4375.95	5.03	15.23
			С	11.6	17.4	2325.2	0.67	0.005
	Bg	100	А	2.3	3.9	256.9	0.59	0.009
			В	8715.6	1241.52	523.8	7.02	16.63
			С	2.3	3.9	256.9	0.59	0.009

Table 2. Comparison of two-phase short-circuit simulation results of two algorithms.

Fault Location	Fault Type	Transition Resistance/ Ω	Phase Sequence	I_r/A	I _{res} /A	I _{RES} /A	K _{sen1}	K _{sen2}
K ₂	D C	0	В	105.5	2637.3	15,662.9	0.04	0.006
	BC	0	С	105.5	2637.3	15,662.9	0.04	0.006 0.006 0.009 0.009 12.1
	BC	100	В	43.0	716.5	4688.6	0.06	0.009
			С	43.0	716.5	4688.6	0.06	0.009
K_4	4.17	0	А	67,309.3	8205.6	5593.5	8.18	12.1
	AB	0	В	18,604	2268	1546	8.18	12.1
	AB	100	А	50,478.3	6678.8	4233.1	7.56	11.8
		100	В	50,478.3	6678.8	4233.1	7.56	11.8

From the calculation results in Tables 1–3, we can get:

(1) For the external fault at the failure phase or the non-fault phase, the braking capacity of the criterion is greater than the braking capacity in Equation (9) and the reliability is higher. For a single-phase ground fault, in the case of high-resistance grounding of the fault phase, the braking amount of the algorithm is at least three times higher than that of the Equation (9) and the protection action is more reliable. For a phase short-circuit fault, in the case of high-resistance ground of the algorithm is at least three times higher than that of the Equation (9) and the protection action is more reliable. For a phase short-circuit fault, in the case of high-resistance grounding of the fault phase, the braking amount of the algorithm is at least six times higher than the braking amount in Equation (9).

(2) For the internal fault, the algorithm proposed in this paper has a better ability to distinguish phases. The braking amount of the fault phase is reduced by 1–3 times than the braking amount in Equation (9) and the sensitivity is relatively high. For single-phase metallic grounding fault, the sensitivity of this algorithm is increased by at least two times for the faulty phase. For the non-faulty phase, the braking capacity is increased by at least 96 times and the reliability is greatly increased. For two-phase short-circuit fault, the sensitivity of this algorithm is increased by 1.6 times for the faulty phase.

It can be seen from Table 3 that for metallic fault, the current transformer at the outlet of the generator is transiently saturated. As the saturation increases, the value of action gradually increases from 90 A to 1069 A and there is still a three-fold margin. When there is a transition resistance with the saturation of the current transformer increases, the value of action gradually increases from 75 A to 809 A, which has a 3.2 times margin, and its reliability is higher than that of metallic faults. The situation shows that this algorithm has a strong ability to resist transient saturation of current transformers.

Fault Location	Fault Type	Transition Resistance/Ω	Saturation θ/(°)	I_r/A	I _{res} /A	Protection Action
		0	30	90	3191	NO
		0	60	293	3191	NO
		0	120	954	3191	NO
V	Δa	0	180	1069	3191	NO
ĸı	Ag	100	30	75	2574	NO
		100	60	235	2574	NO
		100	120	761	2574	NO
		100	180	809	2574	NO

Table 3. Grounding external fault occurs.

5.2. Dynamic Experiments

5.2.1. Experiment System and Its Parameters

For the theoretical analysis and simulation verification of the internal short circuit of the generator's stator, some corresponding experimental studies and verifications were also conducted. The special experimental salient-pole synchronous generator with the device model CSC-300G used in Yuneng Yushen Thermal Power Co., Ltd. (Harbin Electric Factory Co., Ltd., Harbin, China) was selected as the test unit. The main parameters of #1 generator and #2 generator are shown below, and the equivalent wiring diagram of the dynamic simulation experiment is shown in Figure 11.



Figure 11. Equivalent wiring diagram of dynamic model experiment.

Rated apparent power is 733 MVA. Rated voltage U_N is 20 kV. Main transformer capacity is 780 MVA. High-voltage-side primary rated voltage is 242 kV. Low-voltage-side primary rated voltage is 20 kV. Line positive sequence capacitive reactance fixed value is 580 Ω . Line zero-sequence capacitive reactance fixed value is 840 Ω . Load limit resistance fixed value is 46.24 Ω .

5.2.2. Experiment Results and Analysis

A single-phase grounding fault experiment of the stator winding A phase was carried out on the #1 unit. The experimental results are shown in Figure 12 and Table 4.



Figure 12. Waveform diagram of dynamic experiment results.

Fault Location	Fault Type	Transition Resistance/Ω	Phase Sequence	I_r/A	I _{RES} /A	K _{sen2}
	Ag	0	А	273.1	30,344.5	0.009
			В	1.53	305.83	0.005
V			С	2.11	351.67	0.006
ĸ ₁	Ag	100	А	149.1	5140.38	0.029
			В	1.9	168.52	0.011
			С	1.5	130.85	0.012
	Cg	0	А	1.4	274.64	0.005
			В	1.6	316.73	0.005
V-			С	296.3	32,956.3	0.009
K3	Cg	100	А	1.3	59.78	0.021
			В	1.2	56.42	0.021
			С	155.3	5776.1	0.027
	Bg	0	А	91.3	18,356.2	0.005
			В	4145.5	216.93	19.11
<i>K</i> _			С	95.5	19,563.6	0.008
κ ₅	Bg	100	А	94.1	13,442.4	0.007
			В	2311.3	121.37	19.45
			С	93.2	13314.3	0.007

Table 4. Results of calculation data of dynamic model experiments.

Figure 12 shows the waveform collected after the dynamic experiments, and the data can be read from the recorder for protection calculation. Table 4 shows the results of dynamic model experiments. It can be seen from Table 4 that when an external fault occurs, the protection is reliable and does not operate, and the calculation results are basically corresponding to the software simulation results. When the internal fault occurs, the value of the action quantity calculated from the fault phase is greater than that of the control momentum, which meets the requirements of the protection action and is basically corresponding to the results of the software simulation.

From Figure 12 and Table 4, on one hand, dynamic experiments verify the correctness of PSCAD software simulation. In the whole transition process after the fault, the calculation results of the data obtained by PSCAD software simulation are consistent with the calculation results of the dynamic simulation experiment data roughly. On the other hand, verifying the correctness of the theoretical analysis and indicating the proposed generator differential protection method based on the new braking mode can reflect the internal state of the generator accurately.

6. Conclusions

Aiming at the problems of traditional generator differential protection, a more complete, large-scale, turbo-generator model was established, and a new type of braking method for generator differential protection is proposed by using the difference between the current characteristics of the healthy phase and the fault phase. This method is based on the protection characteristics of longitudinal impedance:

For external fault, the current sum at both ends of the winding stator winding is constantly less than the ratio of the voltage phasor difference to the winding impedance, which is significantly less than the set value, so the protection is reliable and does not operate.

For the internal fault, the current sum at both ends of the winding stator winding is constantly greater than the ratio of the voltage phasor difference to the winding impedance, which is obviously greater than the set value, so the protection is sensitive.

According to the simulations and the up-to-date dynamic experiments under different fault conditions, this model took into account the influence of the mutual inductance between the internal windings of the generator and made use of the stator winding method to improve the model parameters. This algorithm has high sensitivity and reliability in both internal and external faults. It has the merits of easy implementation and setting and sensitive action. It also can suppress the impact of current transformer transient saturation effectively and has engineering application value.

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Figure A1. Schematic diagram of overall structure and fault location of 660-MW turbo-generator model.

Appendix A

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