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Analysis and Improvement of Adaptive Coefficient Third Harmonic Voltage Differential Stator Grounding Protection

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Abstract: This paper presents a novel third harmonic voltage differential stator grounding protection (THV-DSGP) method combining the adaptive coefficient and fixed coefficient. It can solve the protection sensitivity degradation problem when the insulation resistance of stator winding to ground is slowly declining. This protection method retains the advantages of the adaptive coefficient, which is to maintain high sensitivity in case of an instantaneous ground fault. Moreover, the fixed coefficient can remember the initial insulation state of the stator winding and prevent relay failure when the stator insulation is slowly declining. In addition, due to zero-sequence voltage disconnection (ZSVD) often leading to malfunctioning of the THV stator ground protection, the existing criterion of the ZSVD was improved according to the electrical characteristics of the generator when ZSVD happens. THV-DSGP with both adaptive coefficient and fixed coefficient was simulated in the Matlab/Simulink. The simulation results show that the proposed protection can be applied to the slow ground fault of the stator winding. Furthermore, the improved criterion of ZSVD can effectively distinguish the stator metal earth fault and the secondary loop break of the zero-sequence voltage.

Keywords: adaptive coefficient; fixed coefficient; third harmonic voltage; stator ground protection; sensitivity; differential; simulation

1. Introduction

In recent years, technology related to power grid-side protection has been significantly improved [1,2], but generator protection as a power-side protection is still crucial in maintaining the safety and stability of the power system. Against the background of the rapid development of power systems, generator protection still has prospects for development.

Single-phase grounding of the stator is a typical generator fault. If the single-phase ground fault of the stator fails to be detected and resolved in time, it may easily lead to phase-to-phase short-circuit or inter-turn short circuit, and even burn down the core. There are many factors that cause stator single-phase ground faults. The literature [3,4] has pointed out that once the cooling water leaks in a water-cooled generator, the water will accelerate insulation deterioration of stator bars by hydrolysis because of the hygrothermal condition. One study [5] describes several causes of stator single-phase ground faults, such as the increase of the conductivity of the cooling water used in the water-cooled generator leading to a decrease in the resistance of the water system to the ground; the cooling water in the stator winding bar is blocked, resulting in local heating and deteriorating the insulation ability of the outer layer; the loosening of the fixture at the stator winding end results in the wear of the outer insulation of the winding being reduced. It can be seen that the single-phase ground fault of the stator is relatively concealed. Moreover, the stator insulation decline process may be long and the stator grounding protection needs to be considered for various factors.

Stator ground protection of large generators usually adopts dual protection configurations. One can use low-frequency power injected stator ground protection, and the other uses fundamental zero-sequence voltage protection combined with the third harmonic voltage protection. In order to reduce the impact of the generator on the earth's capacitive reactance, the frequency of low-frequency injection power is mostly set to 20 Hz or below. At present, there is no single principle of stator ground protection that can completely replace other types of stator ground protection.

Low-frequency power injected stator ground protection measures ground resistance; this protection is not affected when the generator set is shut down. However, the frequency is usually set to 20 Hz and then the time window of the Fourier algorithm for this protection is up to 0.1 s [6], and the inherent delay of tripping is long. Furthermore, when the protection is put into operation, the setting parameters need to be corrected in the field and then the process is quite complicated [7,8]. Therefore, the low-frequency injection current is a small signal for the current transformer (CT) and the operating characteristics of the CT are not ideal in this case, which can result in a large measurement error of grounding resistance after the generator set is put into operation [9]. Fundamental zero-sequence voltage stator ground protection principle is simple, but there is a dead zone near the neutral point, and the neutral point of large-scale generating units are mostly grounded by the grounding transformer, which results in a lower sensitivity of the fundamental zero-sequence voltage protection [10]. At the same time, due to the increase in stator-to-ground capacitance of large units, the low-sensitivity region of the fundamental zero-sequence voltage protection will expand from the neutral point to the middle of the winding [11].

The third harmonic voltage stator grounding protection mainly has two principles: the third harmonic voltage amplitude ratio principle and adaptive coefficient type third harmonic voltage differential principle. The third harmonic voltage amplitude ratio principle can protect the ground fault near the neutral point, but the sensitivity is only high near the neutral point and there is a dead zone in the middle of the stator winding to the generator terminal. Although there is no theoretical dead zone when the third harmonic voltage amplitude ratio principle is combined with the fundamental zero-sequence voltage principle, the sensitivity of the middle of the winding is still not ideal. The adaptive coefficient type third harmonic voltage stator grounding differential protection (THV-DSGP) has high sensitivity in ground faults [12,13]. However, its sensitivity is only calculated during transient ground faults. When the insulation of the stator winding to ground slowly declines, the differential coefficient gradually changes according to the insulation state, so that the differential voltage is continuously cleared; the protection may still fail to operate until the insulation of the stator to ground is completely damaged. In addition, because the third harmonic voltage protection is affected by the zero-sequence voltage disconnection (ZSVD), there are many kinds of malfunctions, so the protection reliability still needs to be improved.

In order to improve the performance of the stator grounding protection, the third harmonic voltage stator ground protection is still being developed [14–16]. One study [14] takes the variation of the third harmonic voltage phase angle difference between the generator terminal and the neutral point as the operating criterion. Researchers [15] constructed a set of third harmonic voltage variation differential protection based on the information characteristics of the third harmonic voltage variation of the generator terminal and the neutral point during normal operation and stator ground fault. One paper [16] proposed the voltage differential criteria using the comprehensive characteristic information of the fundamental zero-sequence voltage and the third harmonic zero-sequence voltage. The above literature provides new ideas for the development of generator stator grounding protection. However, there has been no mention of a situation where the resistance of the stator to ground drops slowly. The rapid identification method of the ZSVD providing for blocking the third harmonic voltage stator ground protection is not mentioned either.

In this paper, the sensitivities of the adaptive coefficient THV-DSGP during the insulation descent at different points of the stator windings are calculated based on the parameters of a 300 MW turbine generator. On this basis, a THV-DSGP combining adaptive coefficient and fixed coefficient is proposed, and the discriminating method of generator's ZSVD is also improved. The protection scheme is simulated in Matlab/Simulink, and the simulation results show that the scheme is correct and the conclusions obtained can provide reference for the improvement of stator grounding protection.

2. Fundamental Analysis of the Third Harmonic Voltage Stator Ground Protection

A common stator-winding double-branch parallel-connected generator is considered as the research object in this paper. The stator winding is a 60° phase band, and each phase has nine windings in a single branch. The third harmonic voltage of each winding has equal amplitude and different phases.

Figure 1a shows the single-phase grounding equivalent circuit of the stator winding of the generator, which is grounded by a grounding transformer. In the figure, C_n is the generator neutral point to ground capacitor, C_s is the generator terminal to ground capacitor, R_g is the ground fault transition resistance, $R_n(sec)$ is the secondary resistance of grounding transformer, G is the grounding point, α is the proportion of the grounding point to the neutral point taking up the entire winding, $\dot{E}_3^{'}$ is the third harmonic potential vector from the neutral point to the ground, $\dot{E}_3^{''}$ is the third harmonic potential vector from the ground to the generator terminal. Figure 1b,c show the fundamental and third harmonic potential vectors of the generator studied in the literature [17], respectively. In Figure 1b, a 60 degree arc is formed by connecting all the fundamental potential vectors of a single turn winding end to end. $\dot{E}_1(\overline{NS})$ is the generator single-phase fundamental potential vector, $\dot{E}_1^{'}(\overline{NG})$ is the fundamental potential vector from the neutral point to the ground, and $\dot{E}_1^{''}(\overline{GS})$ is the fundamental potential vector from the ground to the generator terminal. In Figure 1c, a semicircle is formed by connecting all the third harmonic potential vectors of a single turn winding end to end. $\dot{E}_3(\overline{NS})$ is the generator single-phase third harmonic potential vector, $\dot{E}_3^{'}(\overline{NG})$ is the third harmonic potential vector from neutral point to the ground, and $\dot{E}_3^{''}(\overline{GS})$ is the third harmonic potential vector from the ground to the generator terminal.

According to Figure 1, when grounding occurs in branch 1, the expressions of $\dot{E}_3^{'}$ and $\dot{E}_3^{''}$ are expressed as

$$\left\{\begin{array}{lcl} \dot{E}_3^{'} & = & \frac{1}{2}\dot{E}_3(1 - e^{-j180^{\circ}\alpha}) \\ \dot{E}_3^{''} & = & \frac{1}{2}\dot{E}_3(1 + e^{-j180^{\circ}\alpha}) \end{array}\right. . \tag{1}$$

When grounding occurs on branch 2, $\dot{E}_3^{'}$ and $\dot{E}_3^{''}$ have the following expressions:

$$\left\{\begin{array}{lcl} \dot{E}_3^{'} & = & \frac{1}{2}\dot{E}_3(1 - e^{j180^{\circ}\alpha}) \\ \dot{E}_3^{''} & = & \frac{1}{2}\dot{E}_3(1 + e^{j180^{\circ}\alpha}) \end{array}\right. . \tag{2}$$

Ignoring the leakage impedance and excitation impedance of the grounding transformer, the equivalent circuit of the third harmonic voltage when the generator is in normal operation is shown in Figure 2a. C_f is the total capacitance of the stator windings to ground, C_t is the total capacitance of the generator terminal equipment to earth, $\dot{U}_{3s}$ is the third harmonic voltage vector of the generator terminal, and $\dot{U}_{3n}$ is the third harmonic voltage vector of the generator neutral point, R_n is the equivalent resistance of neutral point to ground and L_n is the equivalent inductance of neutral point to ground.

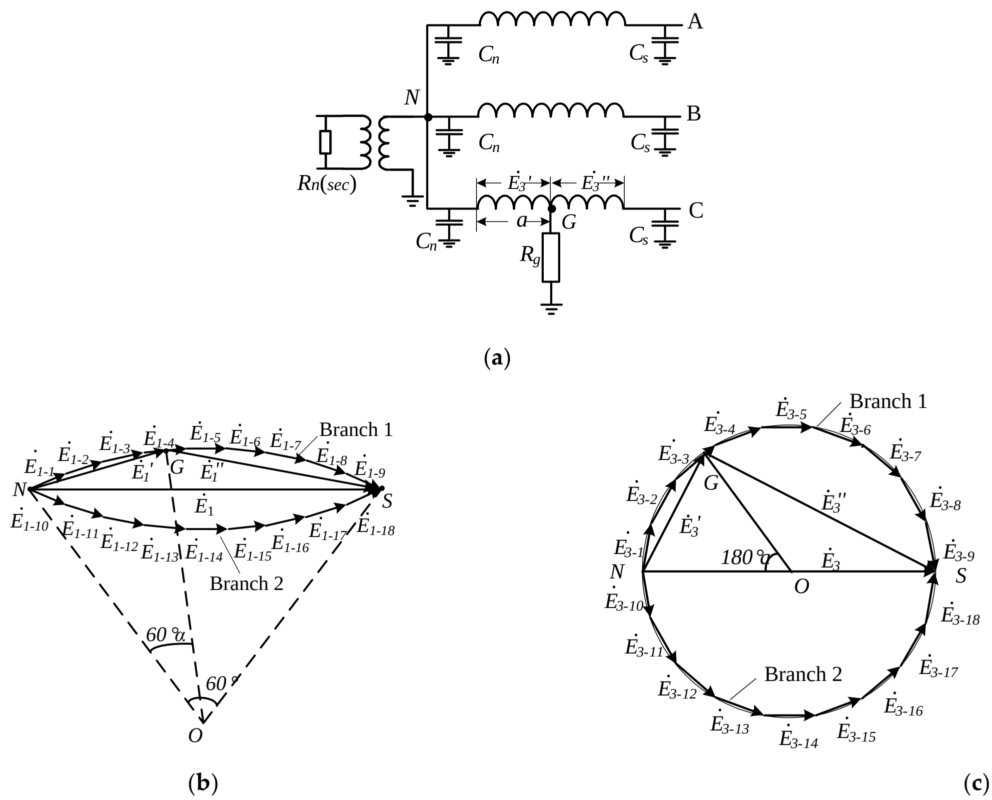

Figure 1. The stator ground equivalent circuit and its third harmonic voltage vector. (**a**) Single-phase grounding circuit of the generator stator; (**b**) The fundamental potential vector when stator grounded (**c**) The third harmonic potential vector when stator grounded.

Ignoring the coupling capacitance between the high and low voltage sides of the main transformer, the generator third harmonic voltage equivalent circuit is shown in Figure 2b when the stator is earthed [14,18]. In Figure 2b, R_g is the grounding resistance of the stator, and Y_1, Y_2, and Y_3 are admittances in each dotted box, and the expressions are given as:

$$\left\{ \begin{array}{lcl} Y_1 & = & \frac{1}{R_n + j\omega_3 L_n} + 0.5j\omega_3 C_f \\ Y_2 & = & j\omega_3 \left(0.5C_f + C_t\right) \\ Y_3 & = & \frac{1}{R_g} \end{array} \right. , \quad (3)$$

where ω_3 is the third angular frequency. According to Figure 2b, the expressions of $\dot{U}_{3s}$ and $\dot{U}_{3n}$ after the single-phase grounding of the stator can be obtained as:

$$\left\{ \begin{array}{lcl} \dot{U}_{3s} & = & \frac{\dot{E}_3 Y_1 + \dot{E}_3'' Y_3}{Y_1 + Y_2 + Y_3} \\ \dot{U}_{3n} & = & -\frac{\dot{E}_3 Y_2 + \dot{E}_3' Y_3}{Y_1 + Y_2 + Y_3} \end{array} \right. . \quad (4)$$

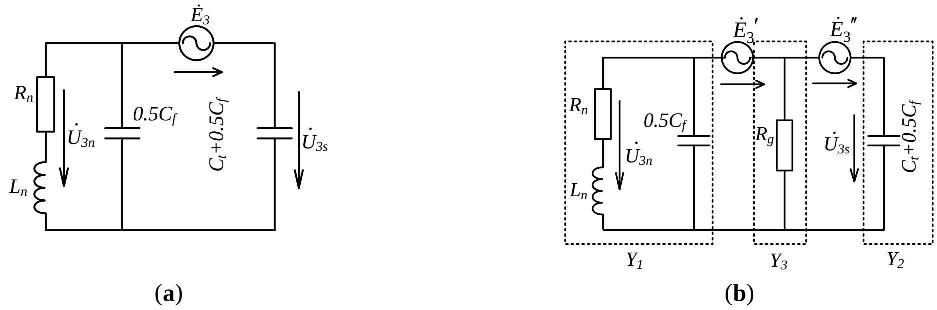

Figure 2. The third harmonic equivalent circuit of the generator. (**a**) Equivalent circuit under the normal operation; (**b**) equivalent circuit when the stator is grounded.

3. Adaptive Coefficient Type THV-DSGP

3.1. Analysis of the Principle of the THV-DSGP with Adaptive Coefficient

The main criterion for adaptive coefficient THV-DSGP is as follows:

$$\begin{cases} \left|\dot{U}_{3n}(t)+\dot{K}_1\dot{U}_{3s}(t)\right| > K_{set1}\left|\dot{U}_{3n}(t)\right| \\ \dot{K}_1 = -\frac{\dot{U}_{3n}(t-\Delta t)}{\dot{U}_{3s}(t-\Delta t)} \end{cases}. \quad (5)$$

In Equation (5), $\dot{U}_{3n}(t)$ and $\dot{U}_{3s}(t)$ are the neutral point third harmonic voltage and the generator terminal third harmonic voltage at the current time, respectively. $\dot{U}_{3n}(t-\Delta t)$ and $\dot{U}_{3s}(t-\Delta t)$ are the neutral point third harmonic voltage and the generator terminal third harmonic voltage at the time before Δt, respectively. $\left|\dot{U}_{3n}(t)+\dot{K}_1\dot{U}_{3s}(t)\right|$ is the differential voltage and $K_{set1}\left|\dot{U}_{3n}(t)\right|$ the braking voltage, respectively.

The normal changes in operating conditions of the generator cause the differential voltage to fluctuate, but not enough to cause the differential criteria to act. The differential coefficient $\dot{K}_1$ is recalculated every time after Δt, so that the differential voltage is cleared to zero. For transient stator ground faults, changes of generator grounding parameters significantly increase the differential voltage and then the voltage differential criterion immediately meet the operating conditions. The program stops updating the adaptive coefficient $\dot{K}_1$ after the differential criterion action is detected, and the protection will act after the trip delay. Considering that there are many factors for ground faults in stator windings, there is a possibility that the insulation may degrade slowly. When the resistance of the stator winding to ground slowly declines, the balance coefficient of the voltage differential criterion gradually follows the insulation change and the protection may still fail to operate until the insulation is completely damaged. In order to solve this problem, the balance coefficient is fixed at the beginning of the operation of the unit, and an action criterion capable of memorizing the initial insulation state is added.

3.2. Sensitivity Analysis of the THV-DSGP Based on Adaptive Coefficient in Stator Insulation Falling Process

By using the grounding parameters of a 300 MW generator, the sensitivity of the adaptive coefficient THV-DSGP is calculated during the stator insulation degradation. The specific parameters are listed in Table 1. ω_1 is the fundamental angular frequency. Braking coefficient K_{set1} is generally in the range of 0.2~0.5 and is set as 0.3 in this paper.

It is assumed that a slight stator ground fault with ground resistance R_{g0} has already occurred at the α point of the stator windings, and the protection has not yet been activated. After that, according to Equations (1)–(5) and the parameters in Table 1, the effective sensitivity of the adaptive coefficient type THV-DSGP at the point α can be calculated. Adjusting α in the range of 0~1, all the corresponding sensitivity values are calculated. The sensitivity curves are shown in Figures 3–5 under three different grounding methods: the ground transformer grounding mode, the Petersen coil grounding mode, and the ungrounded mode, respectively.

Table 1. Parameters of a 300 MW generator.

Name	Value	Instructions
Three-phase total capacitance of stator to ground C_f (μF)	0.528	——
Total capacitance of external equipment on the generator terminal to ground C_t (μF)	0.348	Include absorber capacitance of shock wave on generator terminal 0.3 μF
Total capacitance of stator C_Σ (μF)	0.876	$C_\Sigma = C_f + C_t$
Coupling capacitance between the high and low sides of the main transformer C_M (μF)	0.0047	——
Equivalent resistance of grounding transformer R_n (Ω)	3636	$R_n = 1/(\omega_1 C_\Sigma)$
Equivalent inductance of arc suppression coil L_n (H)	13.89	$L_n = 1.2/(\omega_1{}^2 C_\Sigma)$

As shown in Figures 3–5, it can be observed that the sensitivity of the adaptive coefficient THV-DSGP is not equal in different branches of the stator in the three grounding modes. With the decrease in the initial grounding resistance R_{g0}, the sensitivity on each branch is significantly reduced. Taking Figure 3 as an example, a ground fault occurring at the neutral point (α = 0) is assumed. When the value of the initial grounding resistance changes from +∞ to 20 kΩ, the sensitivity of the protection at this point is about 9 kΩ (point A), which is less than the grounding resistance (20 kΩ), so the protection is not effective; then the grounding resistance drops to 10 kΩ, but the sensitivity of protection at this moment is less than 6 kΩ (point B), so it is still unable to operate; lastly, the grounding resistance is reduced to 5 kΩ. At this moment, the protection sensitivity is only about 4 kΩ (point C). Finally, the protection is still in a refusing state.

From Figures 3–5, it can be seen that the sensitivity of the adaptive coefficient type THV-DSGP grounded by the grounding transformer is the lowest. For the grounding transformer method, according to Equations (1)–(5) and the parameters in Table 1, the sensitivity value can be calculated when the stator winding already has a grounding resistance R_{g0} at α = 0, α = 0.67 and α = 1. Adjusting R_{g0} in the range of 0 to 20 kΩ, the corresponding calculated sensitivity value can be plotted to a curve as shown in Figure 6. According to Figure 6, if the insulation of the stator degrades slowly, the stator grounding resistance does not reach the sensitivity range of the protection, the differential coefficient is recalculated, and the differential voltage is cleared. Thus, the protection is not effective.

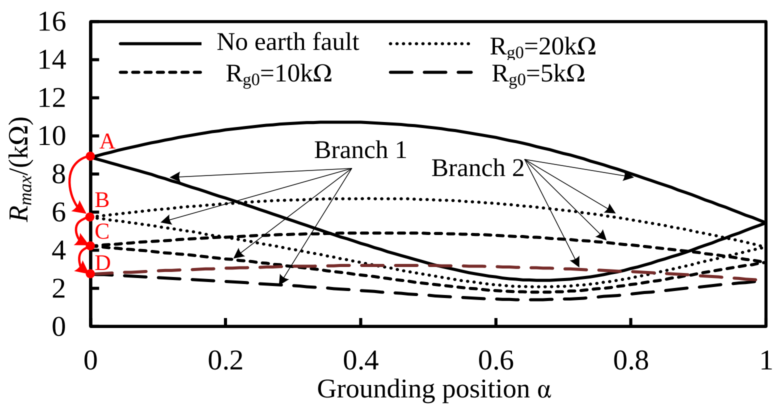

Figure 3. Sensitivity curves of the protection when the stator already grounded by fault resistor R_{g0} under the ground transformer grounding mode.

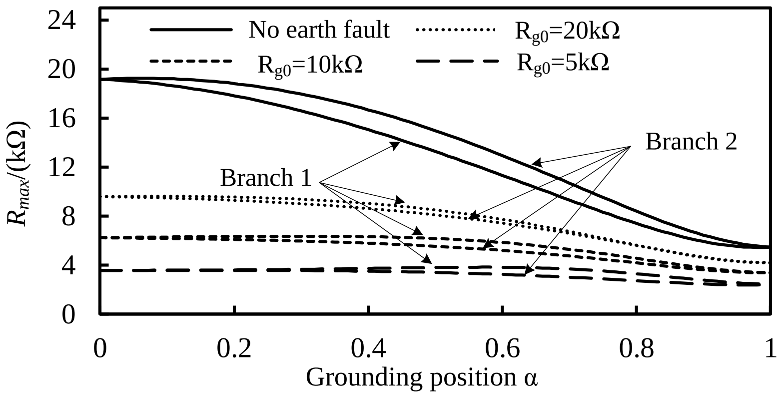

Figure 4. Sensitivity curves of the protection when the stator is already grounded by fault resistor R_{g0} in the Petersen coil grounding mode.

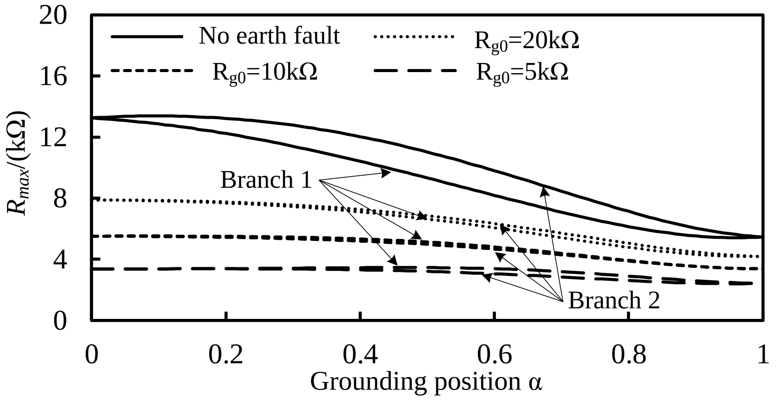

Figure 5. Sensitivity curves of the protection when the stator is already grounded by fault resistor R_{g0} in the ungrounded mode.

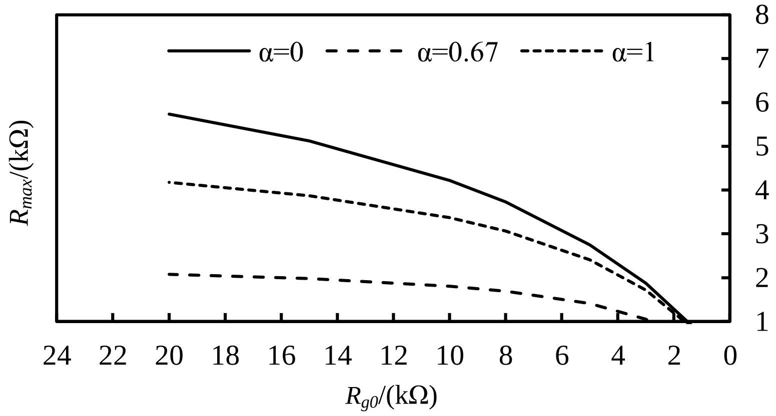

Figure 6. Sensitivity curves of the protection when the stator is grounded by a slowly reduced resistor in the ground transformer grounding mode.

4. THV-DSGP Based on Adaptive Coefficient and Fixed Coefficient

The fixed coefficient is calculated from the initial grounding parameters, and the adaptive coefficient corresponds to the real-time grounding parameters, including the influence of a potential slight grounding fault. Both the adaptive coefficient and the fixed coefficient are used as the balance coefficient of the third harmonic voltage differential criterion. Thus, the differential voltage will be less than the braking voltage and the protection will not malfunction under the normal conditions. When the stator is earthed, the differential voltage is greater than braking voltage and protection can operate correctly.

In the early stage of relay protection, the differential balance coefficient of the THV-DSGP was a fixed coefficient, which was measured when the generator unit was put into operation. After the operating mode changes, the fixed coefficient is not very accurate, but it can basically memorize the initial grounding parameters of the stator windings, and can effectively deal with the stator ground faults with slow insulation drop. At present, the THV-DSGP mostly adopts the principle of adaptive coefficient after the micro-computerization of the relay protection.

In order to expand the applicable range of the THV-DSGP while the protection can be applied to both instantaneous stator ground faults and slow stator ground faults, the adaptive coefficient and the fixed coefficient are simultaneously introduced into the protection. The operation equation of the fixed coefficient THV-DSGP is shown as

$$\begin{cases} \left|\dot{U}_{3n}(t)+\dot{K}_2\dot{U}_{3s}(t)\right| > K_{set2}\left|\dot{U}_{3n}(t)\right| \\ \dot{K}_2 = -\frac{\dot{U}_{3n}(t_0)}{\dot{U}_{3s}(t_0)} = \frac{j\omega_3(0.5C_f+C_t)}{\frac{1}{R_n+j\omega_3 L_n}+0.5j\omega_3 C_f} \\ \dot{K}_2 = K_{2r}+jK_{2i} \end{cases}, \tag{6}$$

where K_{2r} and K_{2i} are the real part and the imaginary part of the fixed coefficient, respectively, and the reference value can be obtained through pre-calculation. Actually, it can be obtained through field measurement. K_{set2} is the braking factor. Equations (5) and (6) together constitute the THV-DSGP combined with self-adjustment coefficient and fixed coefficient. One of the actions shown in Equation (5) or Equation (6) happening will indicate that a stator ground fault has occurred.

The improved protection has a wider applicability, but considering the multiple malfunctions of the third harmonic voltage stator ground protection, the reliability should be improved at the same time. There are many reasons for the fluctuation of the third harmonic voltage of the generator. The main causes include changes in the load of the generator set; the third harmonic voltage of the high voltage side of the main transformer being transmitted to the low voltage side through the coupling capacitor; ZSVD happening at the generator terminal or at the generator neutral point; a short-circuit fault inside or outside the generator affecting the generator armature reaction; or ground faults occurring in the stator windings.

For the case of generator unit load change and the third harmonic voltage change of the high side, the reliability of the protection can be improved by increasing the braking coefficient appropriately. For a short-circuit fault inside or outside the generator, the maximum phase current can be detected. When the phase current is greater than the set value, the protection will be blocked. However, the abnormality of the zero-sequence voltage loop will directly lead to the malfunction of the THV-DSGP. It is necessary to quickly determine whether ZSVD occurs. If the disconnection has occurred, the THV-DSGP must be immediately blocked.

In order to ensure that the THV-DSGP works normally under a certain load and eliminate the influence of short-circuit faults inside or outside the generator on the protection, the commonly used phase current blocking criterion is expressed as

$$\begin{cases} I_{\max} < 0.2I_e \\ I_{\max} > 1.2I_e \end{cases}, \tag{7}$$

where $I_{\max}$ is the maximum phase current of the generator and I_e is the rated current of the generator. When the condition in Equation (7) is satisfied, the new protection is blocked by a short delay of 20 ms. Otherwise, the protection is opened by a long delay of 10 s.

The generator generates a certain third harmonic voltage while generating the fundamental voltage. According to this, the commonly used criterion equation of ZSVD at generator neutral point is expressed as

$$\begin{cases} U_1(t) > 0.9U_N \\ \left|\dot{U}_{3n}(t)\right| < 0.1 \end{cases}, \tag{8}$$

where $U_1(t)$ represents the generator positive sequence voltage and U_N is the generator rated voltage. If Equation (8) satisfies the requirement and lasts for 10 s continuously, it is judged that the secondary voltage circuit of the generator neutral point is broken.

According to Figure 2b, when a metal ground fault occurs at the neutral point, the third harmonic voltage of the neutral point is close to zero, so Equation (8) is also satisfied. Therefore, Equation (8) cannot distinguish between the ground fault and the ZSVD at the neutral point. In addition, the time delay 10 s of the existing voltage loop breakage criterion is too long to block the THV-DSGP in time, so the discriminating method for the ZSVD at the neutral point must be improved.

After the metal ground fault occurs at the neutral point, the third harmonic voltage of the generator is all imposed on the equivalent capacitance of the generator terminal to ground. The third harmonic voltage on the generator terminal will have a significant sudden increase. Therefore, the metal grounding criterion of the generator's neutral point is set as follows:

$$\begin{cases} \left|\dot{U}_{3\mathrm{n}}(t)\right| < 0.2 \\ \left|\dot{U}_{3s}(t)\right| > 0.5 \\ \Delta U_{3s}(t) = \left|\dot{U}_{3s}(t)\right| - \left|\dot{U}_{3s}(t-\Delta t)\right| \\ \Delta U_{3n}(t) = \left|\dot{U}_{3n}(t)\right| - \left|\dot{U}_{3n}(t-\Delta t)\right| \\ \Delta U_{3n}(t) < \min\left\{-0.6 * \left|\dot{U}_{3n}(t-\Delta t)\right|, -0.2\right\} \\ \Delta U_{3s}(t) > \max\left\{0.3 * \left|\dot{U}_{3s}(t-\Delta t)\right|, 0.2\right\} \end{cases}. \tag{9}$$

If both Equations (8) and (9) satisfy the act condition, the metal ground fault of the generator neutral point can be judged, and the protection is not blocked; if Equation (8) satisfies the act condition but Equation (9) does not, it is judged to be the ZSVD at the neutral point, and the protection will be blocked in short delay 20 ms.

Existing criterion of the ZSVD at the generator terminal is usually as follows:

$$\begin{cases} U_1(t) > 0.9U_N \\ \left|\dot{U}_{3s}(t)\right| < 0.1 \end{cases}. \tag{10}$$

If Equation (10) is satisfied for lasting 10 s continuously, the disconnection is determined. According to Figure 2b, after the metal ground fault occurs at the generator terminal, the third harmonic voltage of the generator terminal drops to near zero and the third harmonic voltage at the generator neutral point will have a significant sudden increase. Obviously, Equation (10) cannot distinguish between the generator terminal's metal ground fault and the ZSVD at generator terminal point, but the generator's terminal metal grounding criterion can be set as follows:

$$\begin{cases} \left|\dot{U}_{3s}(t)\right| < 0.1 \\ \left|\dot{U}_{3n}(t)\right| > 0.5 \\ \Delta \mathrm{U}_{3s}(t) < \min\left\{-0.6 * \left|\dot{U}_{3s}(t-\Delta t)\right|, -0.2\right\} \\ \Delta \mathrm{U}_{3n}(t) > \max\left\{0.3 * \left|\dot{U}_{3n}(t-\Delta t)\right|, 0.2\right\} \end{cases}. \tag{11}$$

If both Equations (10) and (11) satisfy the act condition, it is judged to be metal ground fault of the generator terminal, and the protection is not blocked; if Equation (10) satisfies the condition but Equation (11) does not, it is judged to be the ZSVD at the generator terminal, and the protection will be blocked after a short delay of 20 ms.

In summary, the logic diagram of the new protection scheme is shown in Figure 7.

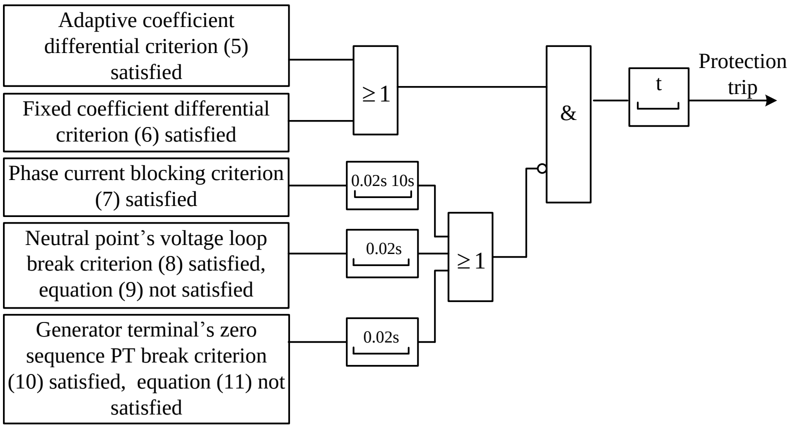

Figure 7. Logic diagram of the new protection scheme.

5. Simulation of the THV-DSGP based on the Adaptive Coefficient and the Fixed Coefficient

A stator grounding simulation model is built in Matlab/Simulink to verify the proposed protection method. The generator is set to be grounded by a grounding transformer. The simplified circuit shown in Figure 8a is used to simulate the single-turn winding of the stator. The whole stator winding model is built based on the internal voltage relationship of the stator winding, as shown in Figure 1.

In Figure 8a, C_1 is the capacitance of the single turn winding to ground, $\dot{E}_{1-n}$ is the fundamental voltage of the nth turn stator winding, $\dot{E}_{3-n}$ is the third harmonic voltage of the nth turn stator winding. Since the resistance of each stator winding and the third harmonic inductive reactance are much smaller than the capacitive reactance of the stator, the winding resistance, and inductance are ignored. Figure 8b shows a schematic diagram of the stator grounding simulation structure. In Figure 8b, $R_n(sec)$ is the secondary resistance of grounding transformer, R_g is the ground fault resistance.

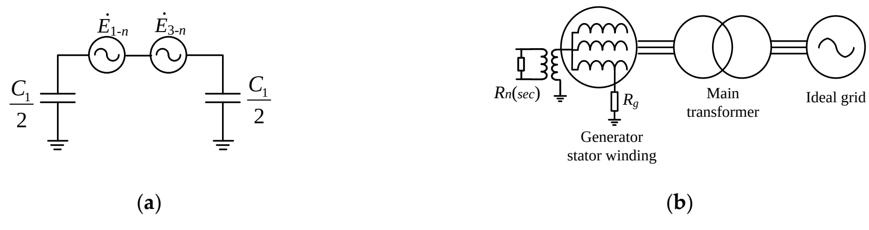

Figure 8. Simplified diagram of the simulation model. (**a**) Simplified model of single turn winding; (**b**) structural diagram of stator ground simulation.

The simulation parameters are set as follows: generator rated voltage is 18 kV, generator terminal PT ratio is 18 kV/100 V/57.74 V, grounding transformer ratio is 18 kV/173 V, $R_n(sec)$ is 0.3362 Ω, main transformer connection mode is YNd11, high side rated voltage is 500 kV, high side PT ratio is 500 kV/100 V/173 V, 3rd harmonic voltage E_3 is 2% of the rated phase voltage, memory time interval Δt is 80 ms. The third harmonic voltage vector is extracted using a half-wave Fourier algorithm with a sampling rate of 2.4 kHz and the braking coefficients K_{set1}, K_{set2} are all taken as 0.3.

A ground fault simulation is performed on branch 1 of the stator winding to simulate a gradual drop in the grounding resistance as shown in Figure 9. A ground fault occurs at 0.6 s and the grounding resistance is 25 kΩ. Then the grounding resistance gradually declines to 1 kΩ. According to the grounding resistance demonstrated in Figure 9, the calculation of the THV-DSGP under the adaptive coefficient and the fixed coefficient is obtained through simulation and the simulation results are shown in Figures 10–12. In the figures, U_{3d1} represents the fixed coefficient differential voltage, U_{3d2} represents the adaptive coefficient differential voltage, and U_{3r} represents the braking voltage.

In Figure 10, a ground fault occurs at the neutral point. When the grounding resistance is 5 kΩ at 1.4 s, the fixed coefficient differential voltage begins to exceed the braking voltage. When the grounding resistance is 1 kΩ at 2.2 s, the adaptive coefficient differential voltage begins to exceed the braking voltage. In Figure 11, a ground fault occurs at $\alpha = 0.67$. When a ground resistance is 1 kΩ at 2.2 s, the fixed coefficient differential voltage begins to exceed the braking voltage. However, the adaptive coefficient differential criterion has not been actuated through the whole process. In Figure 12, earth fault occurs at the generator terminal, the grounding resistance is 4 kΩ at 1.6 s and the fixed coefficient differential voltage starts to exceed the braking voltage. When the grounding resistance is 1 kΩ at 2.2 s, the adaptive coefficient differential voltage starts to exceed the braking voltage.

It can be seen from the simulation results that the fixed coefficient differential voltage is larger than the adaptive coefficient differential voltage when the stator insulation slowly declines. From Figures 10–12, it can be also seen that the amplitude and phase of the third harmonic voltage in the zero-sequence voltage are relatively stable when the neutral point is grounded. However, when α is 0.67 or 1, the amplitude and phase of the third harmonic voltage in the zero-sequence voltage show significant glitches when the grounding resistance changes. This is due to the fact that there is no fundamental voltage in the zero-sequence voltage channel when the neutral point is grounded, and when α is 0.67 or 1, the zero-sequence voltage channel contains a large amount of mutated fundamental voltage.

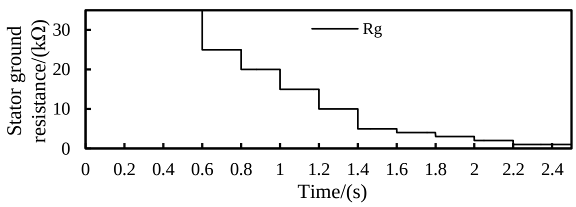

Figure 9. Change process of the stator grounding resistor.

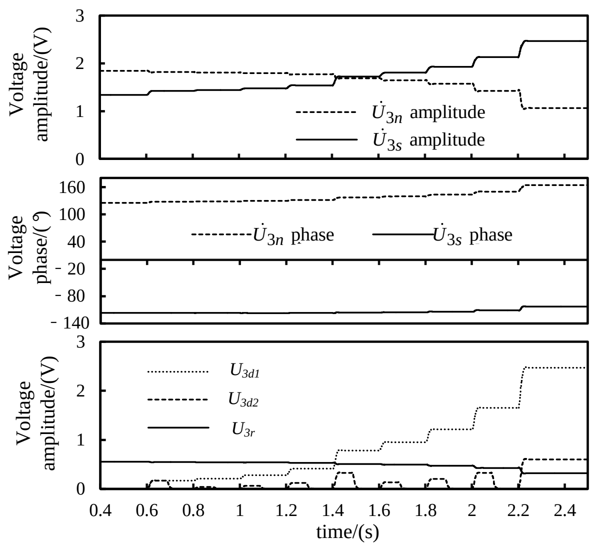

Figure 10. Trip calculation when a generator's neutral point is grounded via a varied resistor.

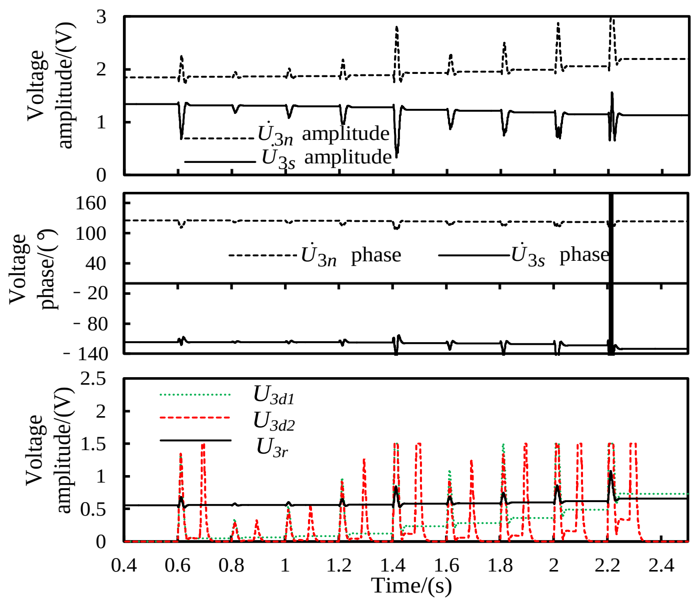

Figure 11. Trip calculation when the winding (somewhere α is 0.67) is grounded via a varied resistor.

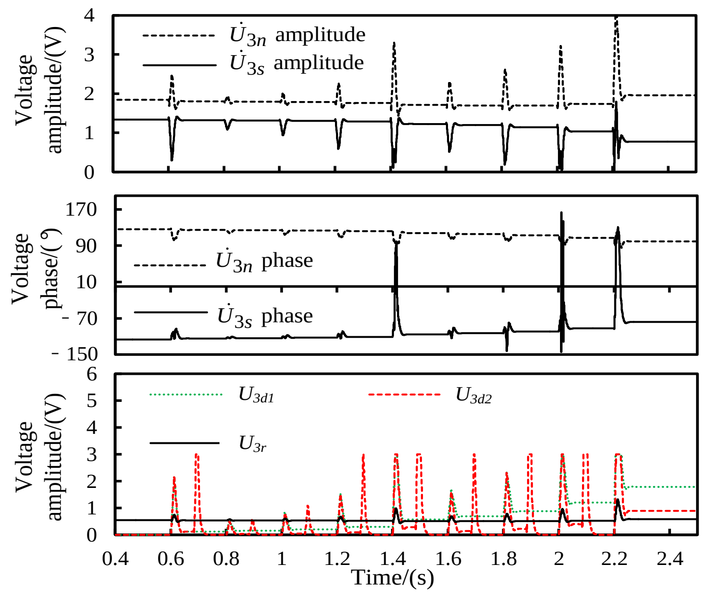

Figure 12. Trip calculation when the generator terminal is grounded via a varied resistor.

When the half-wave Fourier calculation sampling window contains a large number of mutated fundamental voltage, the third harmonic voltage cannot be accurately calculated. In order to avoid malfunction, the protection's action equation should continue to meet 40 ms or more.

At the neutral point of the generator, a metal ground fault is simulated at the time of 0.6 s, and the voltages of the generator are shown in Figure 13. $\dot{U}_n$ is the zero sequence voltage at the generator neutral point, $\dot{U}_s$ is the zero sequence voltage at the generator terminal point.

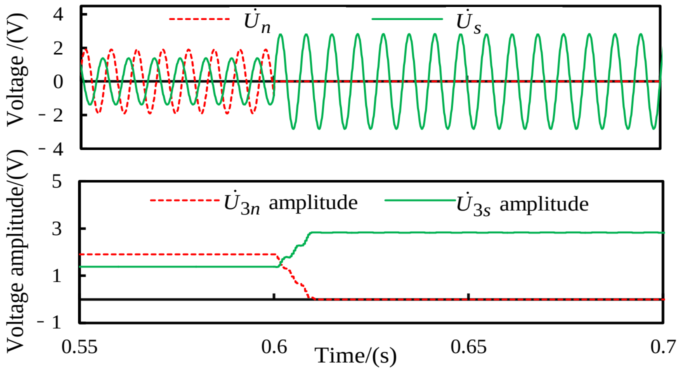

Figure 13. The third harmonic voltage of when a metal ground fault occurs at a generator's neutral point.

As shown in Figure 13, the third harmonic voltage of the neutral point drops to zero after the metal ground fault occurs at the neutral point of the generator. Moreover, the third harmonic voltage of the generator terminal increases significantly. The third harmonic voltage generated by the generator will be imposed on the capacitor of the generator terminal to ground. So Equation (9) will satisfy the operating conditions and the protection will not be blocked.

If it is detected that the third harmonic voltage of the neutral point suddenly drops below 0.1 V, but there is no obvious increase in the zero-sequence third harmonic voltage at the generator terminal, it can be judged as the ZSVD. It can be seen that Equation (9) can distinguish between a neutral metal ground fault and a disconnection of neutral voltage loop.

At the point of generator terminal, a metal ground fault is simulated at the time of 0.6 s, and the voltages of the generator are shown in Figure 14.

As shown in Figure 14, the third harmonic voltage of the terminal point drops to zero after the metal ground fault is occurred. Furthermore, the third harmonic voltage of the generator neutral point increases significantly. So Equation (11) will satisfy the operating conditions and the protection will not be blocked.

If it is detected that the third harmonic voltage of the terminal point suddenly drops below 0.1 V but there is no obvious increase in the zero-sequence third harmonic voltage at the generator neutral point, it can be judged as the ZSVD. It can be seen that Equation (11) can distinguish between a terminal metal ground fault and a disconnection of terminal voltage loop.

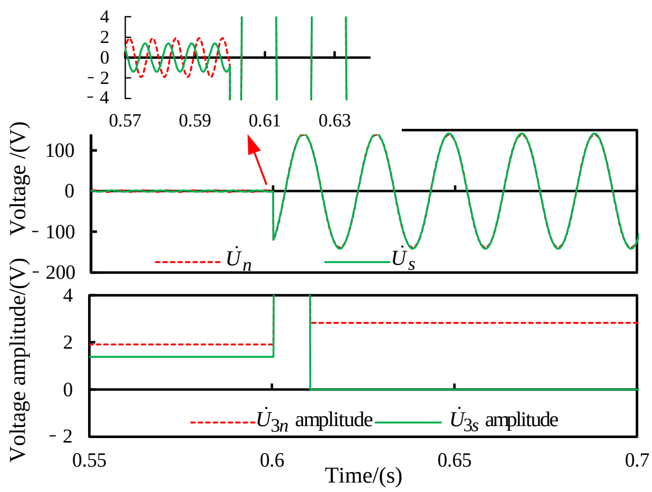

Figure 14. The third harmonic voltage of when a metal ground fault occurs at the generator's terminal.

According to the above simulation analysis, it can be seen that the improved protection can retain the high sensitivity of the adaptive coefficient type THV-DSGP in transient ground faults, and also can be applied to the situation where the stator windings winding insulation slowly degrades. In addition, the protection will not mistakenly trip after the zero sequence voltage circuit is broken.

6. Conclusions

According to the parameters of a 300 MW turbine generator, the sensitivity of the adaptive THV-DSGP is calculated during the process of insulation degradation at different positions of the stator windings. The calculation results show that the original protection may not be able to operate correctly when the slow ground fault occurs on the stator. Based on this, the THV-DSGP combining adaptive coefficient and fixed coefficient is proposed and the ZSVD's criterion for the THV-DSGP is improved. This protection method is simulated in Matlab/Simulink and the simulation results verify the correction of the improved scheme. The specific features of the proposed protection are as follows:

(1) While retaining the advantage of adaptive coefficient THV-DSGP, it can be applied to the fault condition where the stator insulation slowly degrades, and there is no dead zone in the entire stator winding range.
(2) In order to prevent malfunction, the protection can be immediately blocked after the ZSVD has happened at the generator terminal point or at the neutral point.
(3) The third-harmonic vector is calculated by using half-wave Fourier algorithm. Consider that when the stator is grounded, a large number of fundamental voltages may suddenly increase in the generator's zero-sequence voltage. The memory time $\triangle t$ of the adaptive coefficient should be greater than 60 ms, and the voltage differential criterion should continue to satisfy 40 ms or above before the protection is activated.
(4) It is still necessary to study and improve the stability of the third harmonic voltage protection when the generator load changes.

Author Contributions: Y.Z. is in charge of the work listed as: searching literatures; proposing the novel third harmonic voltage differential stator grounding protection method; building the simulation model of the proposed scheme in Matlab/Simulink; making charts and writing the article. Y.L. is in charge of analysis of the simulation results and drawing some charts of this paper. J.S. is in charge of analysis of equations and drawing some charts of this paper. M.B. is in charge of searching related literatures and considering the feasibility and validity of the proposed protection method. H.Z. is in charge of revising and polishing the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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