A Novel Fault Location Method for Generator Stator Grounding Considering Armature Reaction

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Abstract. Stator grounding fault is very common to the large generator, and the accurate fault location can greatly reduce the time of corrective maintenance. However, this problem can be very hard since the structure of the winding is very complex. In this paper, a fault location method for large generator stator grounding considering armature reaction is proposed. Firstly, the fundamental potential distribution of the stator winding and the influence of armature reaction on the measured voltage are analyzed, and the mathematical relationship among fault position, fundamental potential, fundamental voltage and grounding resistance is then constructed. On this basis, the process of the fault location can be established. Finally, the accuracy and efficiency of the proposed method are verified by extensive experiments performed on PSCAD/EMTDC.

1. Introduction

The stator grounding fault, which is caused by the insulation damage between stator winding and iron core, is very common to the large generator. Since the large generator has larger shunt capacitance to earth, the fault current may exceed the capacity of the generator. In order to sensitively respond to grounding fault of stator winding, the 100\% stator ground fault protection must be equipped for all generators with capacity of no less than 100MW. To this end, there are three types of stator grounding protection at present, which are the fundamental zero sequence voltage based stator grounding protection, the third harmonic voltage based stator grounding protection, and the injection-based stator grounding protection\cite{1, 2}.

These protections can remove the fault effectively, however they cannot locate the fault position. In the process of maintenance, the basic principles are as follows: (1) when the fundamental zero sequence voltage is close to 100V, the fault position is considered to be on the terminal side; (2) when the third harmonic voltage based stator grounding protection operates, the fault position is considered to be on the neutral side\cite{3, 4}. Since the grounding resistance of fault windings is small, the fault position can be located by manually measuring the ground resistance of each stator coil and gradually narrowing the measuring range. However, owing to the complex structure of stator windings\cite{5, 6}, this process will take a lot of time. Actually, the existing protection device and its fault recording system have provided abundant information for fault analysis, and making full use of these information to locate the fault position will greatly reduce the time of corrective maintenance.
For this purpose, a stator grounding fault location method for high resistance grounding generator is proposed in [7]. This method locates the fault position by analyzing the relationship between the fault resistance and the fundamental zero sequence voltage, which is provided by the stator grounding protection. Similarly, another method independent of injection-based stator grounding protection is proposed in [8]. This method calculates the fault resistance through the fundamental zero sequence voltage and the generator terminal voltage and then uses the calculated resistance to locate the fault. However, the above two methods neglect the fundamental potential distribution of the stator winding and consider that the potential phase of the turns in a phase is the same, which makes the calculation result deviate from the actual situation. Meanwhile, these methods are not suitable for multi-branch generators. To solve these problems, the winding structure of hydro-generator and turbo-generator is analyzed in [9] and [10] respectively, and the relationship between the fundamental potential phase of each turn is considered to improve the fault location accuracy. A stator grounding protection and fault location method based on fault current is proposed in [11] and [12], which is used to implement adaptive grounding protection scheme and achieves satisfied results.

In summary, although the above research has achieved some results, the influence of armature reaction is not considered, which will lead to large deviation of fault location under heavy load operation. For this reason, a fault location method for large generator stator grounding considering armature reaction is proposed in this paper, which considers the fundamental potential distribution of each branch and the influence of armature reaction on port measure voltage, revises the existing fault location model based on equal-proportional mapping principle, and improves the accuracy of the fault location.

2. The analysis of large generator stator grounding fault location

2.1. The analysis of the fundamental zero sequence voltage

The stator grounding fault is shown in Figure 1, where \( R_f \) is the fault resistance, \( \alpha \) is the ratio of the fault winding turns number to the phase winding turns number, \( C_f \) and \( C_s \) are the phase grounding capacitances of stator and external equipment respectively, \( \tilde{E}_A \), \( \tilde{E}_B \) and \( \tilde{E}_C \) are the generator stator potential, and \( U_f \) is the voltage from the fault point to the neutral point. \( U_n \) and \( I_f \) are the fault voltage and current respectively, and they relationship is given by:

\[
\tilde{U}_n = I_f R_f
\]

(1)

The relationship of each voltage vector is shown in Figure 2, where \( g \) is the earth potential, \( \tilde{U}_{AE} \), \( \tilde{U}_{BE} \) and \( \tilde{U}_{CE} \) are phase voltages respectively. It is important to note that the potential phase of each turn in a phase are different, which means \( U_f \) is not equal to \( \alpha E_A \).

![Figure 1. The wiring diagram for generator stator grounding fault.](image1)

![Figure 2. The vector diagram of the phase voltage.](image2)

According from the Figure 2, the generator phase voltage is given by:
Considering the generator three-phase voltage is symmetrical, and its relationship is given by:
\[ E_a + E_b + E_c = 0 \]  \hspace{1cm} (3)

So, the generator terminal zero sequence voltage is given by:
\[ U_a = \frac{1}{3} (U_{a0} + U_{b0} + U_{c0}) = U_{a0} - U_i = I_r R_t - U_i \]  \hspace{1cm} (4)

For any fault point on stator winding, the zero sequence voltage can be calculated by replacing \( E_a \), \( E_b \) and \( E_c \) with \( k E_a \), \( k E_b \) and \( k E_c \), respectively, where \( k \in (0, 1) \) is the distance coefficient from the fault point to the neutral point, and the result is the same with formula (4). So, from the terminal to the neutral point, the zero sequence voltage on the stator winding is equal everywhere, which means that the equivalence of the distribution grounding capacitance to the centralized capacitance will not lead to errors.

2.2. The calculation of the grounding fault current

When the stator grounding fault occurs, the generator zero sequence equivalent circuit is closely related to the neutral grounding mode. There are three common grounding modes as follows: unearthing mode, arc extinction coil grounding mode and transformer grounding mode, and the zero sequence equivalent circuit is shown in Figure 3.

\[ I_0 = -\frac{1}{3} \omega (C_i + C_o) U_0 \]  \hspace{1cm} (5)

\[ I_s = \left[ \frac{1}{\omega L_0} + j \omega (C_i + C_o) \right] U_s \]  \hspace{1cm} (6)

\[ I_0 = -\frac{1}{3R_s} + j \omega (C_i + C_o) U_s \]  \hspace{1cm} (7)

In formulas (5) to (7), \( U_0 \) is the zero sequence voltage, which is measured by terminal or neutral point voltage transformer. \( L_0 \) and \( R_s \) are device parameters. The accuracy of grounding current calculation mainly depends on the parameters \( C_i \) and \( C_o \). Since the stator winding will be deformed and the external equipment may change during normal operation and failure, \( C_i \) and \( C_o \) will change over time. So, the existing low-frequency signal injection method is considered to acquire \( C_i \) and \( C_o \) accurately in real time[13]. On this basis, the grounding fault current is given by:
\[ I_f = 3I_0 \]  \hspace{1cm} (8)
2.3. The space potential distribution of stator windings

Based on the analysis of the generator stator winding structure, the potential distribution of each turn can be obtained beforehand, including the amplitude $E_i$ and phase $\theta$. In the case of a turbo-generator with stator slot $Z=36$, magnetic pole $2p=2$, and phase belt $p=60^\circ$, the slot potential stellar diagram is shown in Figure 4.

![Figure 4. The star map of the slot potential.](image)

Rod 1 and rod 19 are connected in reverse series to form turn (1,19), and other turns are similar. Starting from the neutral point, the phase A winding is composed of six turns in series, (1,19), (2,20), (3,21), (4,22), (5,23) and (6,24). The potential of each turn is $E_1$, $E_2$, $E_3$, $E_4$, $E_5$, and $E_6$, respectively, as shown in Figure 5. So, for every fault point on stator winding, the $E_i$ and $\theta$ could be calculated, as shown in Table 1. The $E_i$ is the per unit value of $|\hat{E}_A|$, and the fault turn number is counted from the neutral point to the terminal direction.

| Fault turn | $E_i$/p.u. | $\theta$(°) |
|------------|-----------|------------|
| 1          | 0.17      | 25         |
| 2          | 0.35      | 20         |
| 3          | 0.52      | 15         |
| 4          | 0.68      | 10         |
| 5          | 0.85      | 5          |
| 6          | 1         | 0          |

Therefore, through calculating the $E_i$ and $\theta$ based on the data provided by the protection and looking up the corresponding value in Table 1, the fault turn could be located.

For the large generators with multi-branch winding structure, although the synthetic potential of each branch in a phase is the same, the positions of the turns that make up the branches may be different. In other words, the “end point” of each branch is the same, but the “path” is different. In the case of two-branch generator with different “path”, the potential vector is shown in Figure 6. It can be seen that the combined values of $E_i$ and $\theta$ corresponding to each turn are unique, and the fault turn can still be located in the same way.

![Figure 6. The potential vector of two-branch generator with different “path”.](image)

![Figure 7. The distribution diagram of the generator stator potential.](image)
2.4. The fault location method for large generator stator grounding

As shown in Figure 1, the electrical quantity that most directly reflects the fault position is the voltage from the fault point to the ground, which is given by:

\[ U_f = I_f R_f - U_o \]  

(9)

where \( I_f \) is calculated from formula (8), \( R_f \) is measured by injection-based protection device, \( U_o \) is obtained from voltage transformer. In this basis, the voltage from the fault point to the ground \( U_f \) can be calculated.

Obviously, in the no-load state, the voltage from the fault point to the neutral point \( U_f \) is the same as the potential \( E_f \), which will not affect the location performance. However, in the load state, since that the load current is much larger than the fault current, the armature reaction cannot be neglected. So, the \( U_f \) is different from the \( E_f \), which leads to the location error of existing methods in load state.

To construct the relation between \( U_f \) and \( E_f \), the phase voltage \( O U_f \) and the phase potential of generator in load state is introduced, where \( O E_f \) could be calculated by the generator initial operation state. Assuming that the effect of armature reaction on the voltage drop of windings is linear, the potential distribution is shown in Figure 7, and the mathematical relationship between \( U_f \) and \( E_f \) can be found based on the equal proportion mapping mechanism, which is given by:

\[ E_f = U_f \times \frac{E_{e_0}}{U_{e_0}} \]  

(10)

In practical application, since the fault phase voltage is the lowest when fault happened, the fault phase can be determined by comparing three-phase voltage. On this basis, through calculating \( E_f \) and looking up the corresponding value in the \( E_e \) table, the fault phase, branch, and turn could be located, which will greatly reduce the time of corrective maintenance.

2.5. Algorithm flow of large generator stator grounding fault locations

In conclusion, the algorithm flow of new large generator stator grounding fault location method is shown in Figure 8. In order to be easily implemented in microcomputer protection devices, the voltage or potential vector diagram could be expressed by the collection of the voltage or potential vector of each turn in stator windings. When \( U_{e_0} \) is between two adjacent vectors, it indicates that the fault position is within this turn. Meanwhile, \( U_{e_0} \) can be expressed as a linear combination of this two vectors, which could locate the exact fault position in the turn.

As it shown in the Figure 8, based on the distribution characteristics of longitudinal voltage from any point in windings to neutral point, this method can be applied to any generator and any operation state, and can realize the fault location in real time without shutdown. In addition, this method can be realized only needed injection-based stator grounding protection device and terminal voltage and current transformer equipment, which is easy to be popularized and applied.

3. Simulation and analysis

3.1. The construction of simulation model

Based on the PSCAD/EMTDC simulation platform, in case of a actual large generator stator winding distribution and the generator operation state, the generator stator grounding fault quasi-distributed parameter model is built[10], as shown in Figure 9. The model has the same physical structure as the actual generator. Each phase consists of 8 branches in parallel, each branch consists of 35 unit circuits in series, and each unit circuit represents a turn. Each turn consists of the fundamental potential, the third harmonic potential, the synchronous reactance, the resistance and the grounding capacitance.

The synchronous reactance equals the average of the direct-axis synchronous reactance and the quadrature-axis synchronous reactance. The phase of the fundamental potential is determined based on the stator winding structure and its amplitude is adjusted to make the terminal voltage rated. The phase
of the third harmonic potential is determined in the same way and its amplitude is 15% of the fundamental potential amplitude.

Forming the potential vector distribution diagram based on the generator stator winding structure

Measuring the voltage and current at generator terminal

Calculating the voltage vector distribution diagram in this operation state

Fault happened?
Yes

Calculating the $E_i$

Locating the fault position based and calculating $\alpha$

Figure 8. The algorithm flow of new large generator stator grounding fault location method.

Figure 9. The generator stator grounding fault quasi-distributed parameter model.

The high resistance grounding generator with the grounding transformer and is connected to loads through the boost transformer, which can simulate the no-load and load operation state. As it shown in Figure 9, $S$ is a fault control switch, and $R_i$ is fault resistance. The generator parameters are: $S_n=888.9\text{MVA}$, $U_n=20\text{kV}$, $X_d=1.036\text{p.u}$, $X_f=0.788\text{p.u}$, $C_1=3.846\mu\text{F}$, $C_2=0.405\mu\text{F}$, $Z_a=(317.35+196.28)\Omega$. The boost transformer parameters are: $S_r=888.9\text{MVA}$, $X_v=0.1846\text{p.u}$, $k=500/20$, and the winding are in YNd11 connection.

3.2. Simulation analysis of fault location method
The simulation testing conditions are as follow: (1)generator operation state: heavy-load $P=750\text{MW}$, $Q=350\text{Mvar}$; light-load $P=388\text{MW}$, $Q=163\text{Mvar}$ no-load; no-load; (2)fault position: neutral point, $\alpha=0$; 10 turns from neutral point, $\alpha=28.6\%$; 20 turns from neutral point, $\alpha=57.1\%$; generator terminal, $\alpha=100\%$; (3)grounding fault resistance: $R_i=5\text{k}\Omega$; $R_r=0\text{k}\Omega$. The simulation results are shown in Figure 10.

In these figures, the real line vector is the voltage distribution of each turn in fault phase windings, which is pointed from the neutral point to the machine terminal and calculated by terminal voltage and current, and each segment vector is the voltage of adjacent 5 turns in series. The dotted line is the transient calculation results obtained by the fault location method proposed in this paper. Each point on the dotted line is the end of the voltage vector from the fault point to the neutral point in real time, and the dotted arrow points to the end of the steady voltage vector. By comparing the steady voltage vector and the real line vector, the final fault position can be located. As the results show, this method can accurately locate the faults position in the whole stator windings with different grounding resistances and different operation state, and has good adaptability.

In addition, since only the steady-state fundamental component is needed in this method, such as the zero sequence voltage, the transient process and data processing methods will affect the calculation of it, including the decaying DC component, abundant harmonic component, the digital filtering and the algorithms, which makes it impossible to locate the fault position within two cycles on power frequency basis. However, since the grounding fault protection usually has at least 0.3-0.5s delay in setting, the short-term error of calculation will not affect the correct operation of the whole stator grounding protection scheme.
Figure 10. The fault location process: (a) heavy-load, $R_i=5k\Omega$; (b) heavy-load, $R_i=0k\Omega$; (c) light-load, $R_i=5k\Omega$; (d) light-load, $R_i=0k\Omega$; (e) no-load, $R_i=5k\Omega$; (f) no-load, $R_i=0k\Omega$.

Figure 11. The fault location result comparison under different operation state.

4. Conclusion
In order to realize the fault location for generator stator grounding and reduce the time of corrective maintenance, a stator grounding fault location method for large generator considering armature reaction is proposed in this paper, which considers the fundamental potential distribution of each
branch and the influence of armature reaction on port measure voltage, revises the existing fault location model based on equal-proportional mapping principle, and improves the accuracy of the fault location. The simulation result shows that this method can accurately locate the faults position in the whole stator windings with different grounding resistances and different operation states. In addition, this method can be realized only needed injection-based stator grounding protection device and terminal voltage and current transformer equipment, which is easy to be popularized and applied.

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