Research on the New Open-phase Protection Criterions for the Generator Circuit Breaker

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Abstract. In 2012, Guangzhou Pumped Storage Power Station A (GPSPSA) once had an serious accident. The generator circuit breaker (GCB) had the open-phase fault when the generator ran with low load. The relevant protection failed to remove the fault and lead to expand the accident scope. Through the comparative analysis of the inverse time negative sequence current protection and the phase angle difference protection of the zero sequence fundamental voltages between GCB both sides, the compound protection based on the zero sequence voltage and the negative sequence current is put forward. Considering the phase and amplitude features of the zero sequence fundamental voltages between GCB both sides, new criterions of the GCB open-phase protection based on the zero sequence voltage amplitude ratio and phasor difference are given. GCB open-phase protection is further optimized by these new protection criterions and can be applied in the relevant power plants.

Introduction

In 2012, GPSPSA once had the serious accident because of the GCB open-phase. In the accident, the 3rd generator of GPSPSA cannot be completely closed and is always run in the open-phase state because A-phase of GCB is broken. After 20 seconds of grid-connect, the zero sequence overvoltage protection at the low voltage side of the 3rd main transformer acted firstly. Then, the 500kV switches of the grid, the 3rd and 4th main transformers, and the 3rd generator are cut off which expanded the scope of the accident.

The high voltage circuit breakers usually operate with split phase which use itself auxiliary contacts to judge the open-phase fault with the currents such as the negative sequence current being auxiliary criterions. But GCB is always a three-phase linkage circuit breaker [1] and there are no auxiliary contacts to build the open-phase protection. In addition to this, the fault current in the case of the open-phase fault is very small and instable when the generator runs with the light load. The action time of the inverse time negative sequence current protection which responses the open-phase fault is too long. It easily leads to the non-selective action of the backup protection in the adjacent line and expands the scope of the fault [2].

The open-phase fault of GCB will cause the serious damage the generator and transformer [3]. So it is necessary to research on the new and fast criterions for the GCD open-phase protection.

Present Situation of GCB Open-phase Protection

Inverse Time Negative Sequence Current Protection

When the symmetric state of the system or generator is destroyed, the negative sequence current flows through the stator winding of the generator will increase. When the product of the square of the negative sequence current per-unit value and duration reaches the certain value, the local area with larger contact resistance of the generator rotor tends to overheat and cause damage [4].

The operation criterion of the inverse time negative sequence current protection with the negative sequence current as protection criterion is
Among them, \( t \) is the action time of the protection. \( A \) is the heating constant of the generator short time negative sequence rotor. It is always given in the equipment parameters and the unit is second. \( I_i \) is the per-unit value of the generator negative sequence current. \( I_{\infty} \) is the per-unit value of the generator negative sequence current allowed for a long time.

The characteristic of the inverse time negative sequence current protection is shown as Fig.1.

![Figure 1. The operation characteristic curve of the generator inverse time negative sequence current protection](image)

The delay of the inverse time negative sequence current protection is entirely decided by the allowable heating limit of the generator rotor. At the same time, there are no misoperation problems caused by the disconnection of the potential transformer (PT) when the negative sequence current is used as the protection criterion.

**GCB Open-phase Protection Based on the Phase-angle Difference of Zero Sequence Fundamental Voltages between GCB Two Sides**

According to the analysis of the related theory, simulation and experiment, the GCB open-phase fault will result in the inequality between the zero sequence fundamental voltage at the generator terminal and the zero sequence fundamental voltage at the low voltage side of the main transformer. The GCB open-phase protection criterion based on the phase-angle difference of the zero sequence fundamental voltages between GCB two sides is put forward [5].

\[
\begin{align*}
\min(U_A, U_B, U_C, U_{TA}, U_{TB}, U_{TC}) &> 80\%U_{phN} \\
\min(U_{phT}) &> U_{\text{set}} \\
|\varphi_{\text{set}} - \varphi_T| &\geq \varphi_{\text{set}} \\
t_{\text{op}} & = 0.5s
\end{align*}
\]

(2)

\( U_A, U_B, \) and \( U_C \) are the effective values of the three phase voltages at the generator terminal. \( U_{TA}, U_{TB} \) and \( U_{TC} \) are the effective values of the three phase voltages at the low voltage side of the main transformer. \( U_{\text{phN}} \) is the effective value of rated phase voltage of the generator. \( U_{\text{set}} \) is the effective value of the zero sequence fundamental voltage at the generator terminal. \( U_{\text{set}} \) is the effective value of the zero sequence fundamental voltage at the low voltage side of the main transformer. It is necessary to set the effective threshold value of the zero sequence fundamental voltage (\( U_{\text{set}} \)) when the GCB open-phase protection starts in case of the misoperation. \( \varphi_{\text{set}} \) is the phase angle of the zero sequence fundamental voltage at the generator terminal. \( \varphi_T \) is the phase angle of the zero sequence fundamental voltage at the low voltage side of the main transformer. \( \varphi_{\text{set}} \) is the operation value of the phase-angle difference of the zero sequence fundamental voltages between GCB two sides and is about 60°. \( t_{\text{op}} \) is the operation time-delay of the new criterion. It needs to match the operation time-delay of the generator stator grounding protection and is considered to remove the fault fastly.

The open-phase protection based on the zero sequence fundamental voltages between GCB two sides can operate sensitively for the GCB open-phase fault when the generator runs with low load. If one phase of PT occurs to disconnect at the generator terminal or at the low voltage side of the main transformer.
New Open-phase Protection Criterions of GCB

According to the existing characteristics of the GCB open-phase protection, the zero sequence fundamental voltages between GCB two sides and the negative sequence current can be considered to form the compound criterion for the generator runs with low load and the heavy load under the condition of the GCB open-phase fault. In addition to the phase-angle difference, other protection criterions based on the zero sequence fundamental voltages between GCB two sides are put forward.

Compound Criterion of Zero Sequence Fundamental Voltages between GCB Two Sides and Negative Sequence Current

When the generator runs with low load, the phase current is small and the current transformer (CT) cannot measure the value exactly. The phase-angle difference of the zero sequence fundamental voltages between GCB two sides is adopted as the criterion of the GCB open-phase protection.

When the generator runs with heavy load, there is no measure problems of CT. So the negative sequence current is adopted as the other one criterion of the GCB open-phase protection.

Assuming the three phase voltages of the generator are completely symmetrical, the three phase capacitance to ground at the generator terminal three are exactly same and the three phase capacitance to ground at the low voltage side of the main transformer are also same. The single-machine infinite system model is built with the disconnection of A phase shown as Fig.2.

The symmetric component method and the superposition principle are used to analyze the GCB open-phase fault [6]. The complex sequence network in the GCB open-phase fault is shown as Fig.3.

Figure 2. The circuit diagram of GCB open-phase fault. Figure 3. The complex sequence network.

In the figure 2 and figure 3, \( x_{10}, x_{20} \) and \( x_{00} \) are the positive, negative and zero sequence reactance of the generator. \( x_{1i} \) and \( x_{2i} \) are the positive and negative sequence reactance of the transformer. \( x_{1s} \) and \( x_{2s} \) are the positive and negative sequence reactance at the system side. \( \Delta U_{10}, \Delta U_{20} \) and \( \Delta U_{00} \) are the positive, negative and zero sequence voltage of the disconnection location. \( i_{10}, i_{20} \) and \( i_{00} \) are the positive, negative and zero sequence current in the fault. \( R_{g} \) is the earthing resistance of the generator neutral point. \( x_{ci} \) is the parallel reactance at the generator terminal. \( x_{c2} \) is the parallel reactance at the low voltage side of the main transformer.

When the GCB occurs the open-phase fault, the negative sequence current is calculated.

\[
i_{20} = -\frac{i_{10}}{1 + \frac{Z_{10}}{Z_{11}} + \frac{Z_{20}}{Z_{21}}}
\]  

(3)
\( I_L \) is the load current when the system runs normally. \( Z_{1g}, Z_{2g} \) and \( Z_{0g} \) are the positive, negative and zero sequence impedance of the disconnection location and the expression is shown as formula 4.

\[
\begin{align*}
Z_{1g} &= \frac{X_{c1}X_{c1}}{j(X_{g1} - X_{c1})} + \frac{X_{c1}(X_{g1} + X_{c1})}{j(X_{g1} - X_{c1})} \\
Z_{2g} &= \frac{X_{c1}X_{c1}}{j(X_{g2} - X_{c1})} + \frac{X_{c1}(X_{g2} + X_{c1})}{j(X_{g2} - X_{c1})} \\
Z_{0g} &= \frac{X_{c1}(X_{g0} - jX_{c1})}{jX_{c1}} - \frac{X_{c1}(X_{g0} - X_{c1})}{jX_{c1}}
\end{align*}
\] (4)

Under the condition of \( Z_{1g} \approx Z_{2g} \) and \( Z_{0g} \gg Z_{2g} \), \( I_{2n} \approx -I_L / 2 \) can be got. When \( I_L \) reaches the 50% rated current, \( I_{2n} \) is about 0.25. The compound criterion formed with the phase-angle difference of the zero sequence fundamental voltages between GCB two sides and the negative sequence current is shown as formula 5.

\[
\begin{align*}
\min(U_A, U_B, U_C, U_{T_A}, U_{T_B}, U_{T_C}) &> 80\% U_{phN} \\
\min(U_{G0}, U_{T0}) &> U_{0 \text{set}} \\
|\phi_{G0} - \phi_{T0}| &\geq \phi_{0 \text{set}} \quad \text{or} \quad I_2' \geq I_2'^{\text{set}} \\
t_{\text{op}} &= 0.5s
\end{align*}
\] (5)

\( I_2'^{\text{set}} \) is the operation value of the negative sequence current in the protection and is about 0.25.

When the system runs normally, the phase-angle difference of the zero sequence fundamental voltages between GCB two sides and the negative sequence current are zero. With the generator load larger, the phase-angle difference of the zero sequence fundamental voltages between GCB two sides will be a large and stable value in the GCB open-phase fault. At the same time, the negative sequence current becomes a large value when the load exceeds the 50% rated load. So using the double criterion will improve the reliability of the protection.

If the generator occurs the grounding fault, the phase voltage of the grounding phase will be zero. It is not satisfied the condition of the criterion and the protection will not start.

**Effective Value Ratio Criterion of Zero Sequence Fundamental Voltages between GCB Two Sides**

Compared to the normal system, the zero sequence fundamental voltage at the generator terminal and the zero sequence fundamental voltage at the low voltage side of the main transformer change obviously in the GCB open-phase fault. In addition to the phase-angle difference, the amplitude difference of the zero sequence fundamental voltages between GCB two sides can be considered. The protection criterion is shown as formula 6.

\[
\begin{align*}
\min(U_A, U_B, U_C, U_{T_A}, U_{T_B}, U_{T_C}) &> 80\% U_{phN} \\
\min(U_{G0}, U_{T0}) &> U_{0 \text{set}} \\
\frac{U_{G0}}{U_{T0}} &= \eta_{0 \text{set}} \\
t_{\text{op}} &= 0.5s
\end{align*}
\] (6)

\( \eta_{0 \text{set}} \) is the operation value of the effective value ratio of \( U_{G0} \) and \( U_{T0} \).

When the system runs normally, the effective value ratio of the zero sequence fundamental voltages between GCB two sides is about 1.0. When GCB occurs the open-phase fault, the effective value ratio of the zero sequence fundamental voltages between GCB two sides will be the value greater than 1.0.
Effective Value of Phasor Difference Criterion of Zero Sequence Fundamental Voltages between GCB Two Sides

In addition to the phase-angle difference and the amplitude difference of the zero sequence fundamental voltages between GCB two sides, the effective value of the phasor difference can also be considered. The protection criterion is shown as formula 7.

\[
\begin{align*}
\min(U_A, U_B, U_C, U_{TA}, U_{TB}, U_{TC}) &> 80\% U_{ph,N} \\
\min(U_{G0}, U_{T0}) &> U_{0,\text{set}} \\
|\hat{U}_{G0} - \hat{U}_{T0}| &\geq K_{0,\text{set}} \\
t_{\text{op}} & = 0.5s
\end{align*}
\]

(7)

\(\hat{U}_{G0}\) and \(\hat{U}_{T0}\) are the zero sequence fundamental voltage at the generator terminal and the zero sequence fundamental voltage at the low voltage side of the main transformer. \(K_{0,\text{set}}\) is the operation value of the effective value of the phasor difference of \(\hat{U}_{G0}\) and \(\hat{U}_{T0}\) and can be set about 2V.

When the system runs normally, \(\hat{U}_{G0}\) and \(\hat{U}_{T0}\) are same and their phasor difference is zero. When GCB occurs the open-phase fault, \(\hat{U}_{G0}\) and \(\hat{U}_{T0}\) become different and their effective value of the phasor difference will be a large value with the generator load larger. The protection device measures the three phase voltages and the zero sequence voltages at the generator terminal and the low voltage side of the main transformer and calculates their effective values of fundamental voltages. Once the valves are satisfied with the protection criterion, the GCB open-phase protection will start and alarm or trip after the time-delay.

Conclusion

(1) In the case of the low load and heavy load of the generator, the inverse time negative sequence current protection and the GCB open-phase protection based on the phase-angle difference of the zero sequence fundamental voltages between GCB two sides are analyzed relatively aimed at the different electrical characteristics of the GCB open-phase fault. The compound criterion formed with the phase-angle difference of the zero sequence fundamental voltages between GCB two sides and the negative sequence current is proposed to solve problems of the GCB open-phase fault in the different working state. It is useful to improve the reliability and sensitivity of the open-phase protection.

(2) When GCB occurs the open-phase fault, the zero sequence fundamental voltages at the generator terminal and at the low voltage side of the main transformer change obviously. Based on the difference of their phase-angle, amplitude and phasor, the new open-phase protection criterions are proposed. When the generator runs with low load, the new criterions can avoid the lack of the current sensitivity in the open-phase fault. The further improvement and optimization of the GCB open-phase protection will improve the stability and safety of the generator-transformer and the system.

The GCB open-phase protection based on the above new criterions is applied in GSPSPA. The running state is stable and reliable and it can be popularized and applied in relevant power plants.

References


