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Substation Area Backup Protection Algorithm for Phase Comparison of Segregated Current Fault Component

Jianwen Zhao, Junming Zhang, Yanqing Zhang

Xian University Of Science And Technology, Xian, China

Corresponding author's e-mail: 1598369309@qq.com

Abstract. Substation area backup protection currently only relies on the traditional relay protection principle, and does not fully exploit the inherent fault characteristics in the multi-source data of the station domain. In response to these problems, this paper proposes a substation area backup protection algorithm for phase comparison of segregated current fault component. The algorithm takes all electrical elements in the substation station as the protection object. In light of the phase relationship between external faults and internal faults of the protected electrical elements, the phase relationship is quantified and the fault elements are identified according to the quantified results. A typical 220 kV intelligent substation model was built by using electromagnetic transient software PSCAD. The different fault types, fault locations and transition resistance operating states were simulated. The results show that the fault recognition method based on substation area backup protection for phase comparison of segregated current fault component is accurate and effective.

1. Introduction

With the continuous development of smart grid construction, China's power grid gradually develops toward high voltage, large capacity, increasingly complex grid structure, AC-DC hybrid. The operation and control characteristics of the system are becoming more and more complex, and the risk of large-scale system losing stability due to faults is increasing[1]. In this context, the traditional backup protection, which is adjusted according to the stepwise principle, has the defects of difficulty in setting and matching, long action delay, and easy to cause cascading trip when the flow is transferred[2].

Substation area backup protection is a new type of relay protection. Current research on substation area protection mainly includes the following aspects: research on substation area protection scheme based on current differential principle[3], proposed substation area protection based on direction comparison principle[4] and proposed substation area protection based on multi-agent technology[5] and proposed substation area protection based on grey correlation degree[6]. Station domain protection can easily acquire all the information of local protection action. A substation area backup protection scheme based on current protection fusion reliable factor is proposed[7].

In order to overcome the inherent defects of traditional backup protection and maximize the intrinsic fault characteristics of multi-source data in the substation area, in this paper, a fault recognition algorithm based on substation area backup protection for phase comparison of segregated current fault component is proposed. The simulation results show that the fault recognition algorithm of the substation area backup protection is not affected by different operation states such as fault type, fault location and transition resistance.



2. Principle of substation area backup protection fault recognition based on phase comparison of segregated current fault component

According to the superposition theorem, the fault system can be decomposed into normal operation state and additional state in case of failure.

Figure 1 shows the fault component additional network when the fault occurs in the protected electrical element area of the substation, and Figure 2 is the fault component additional network when the fault occurs outside the protected electrical element area of the substation. The power marked “ Δ ” in the figures are the fault component. In Figures 1 and 2, Z_m and Z_n are the system impedance on the M side and N side respectively. Z_b (Z_{bm} and Z_{bn}) are the equivalent impedance of the internal and external faults of the protected electrical elements in the substation. Z_f is the transition impedance.

$-\Delta \dot{E}_f$ is the additional potential of the fault point. $\Delta \dot{U}_m$, $\Delta \dot{U}_n$ and $\Delta \dot{U}_{f0}$ are fault component voltages of M side, N side and fault point respectively. $\Delta \dot{I}_m$, $\Delta \dot{I}_n$ and $\Delta \dot{I}_f$ are fault component currents of M side, N side and fault point respectively. The fault component power is obtained by subtracting the power before the fault from the power after the fault.

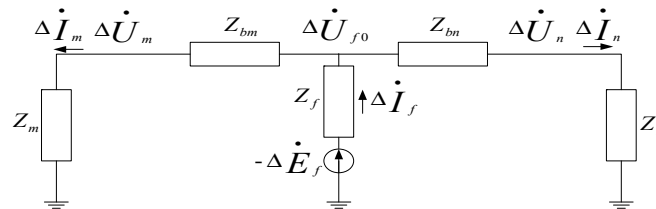


Figure 1. Internal fault component network of protected electrical elements in substation

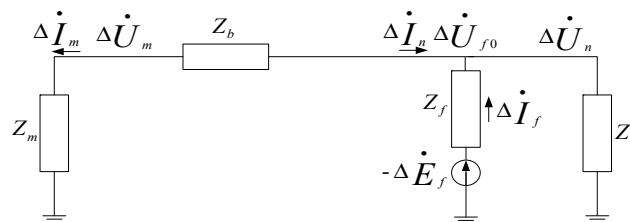


Figure 2. External fault component network of protected electrical elements in substation

2.1 Analysis of segregated current fault component in the internal fault of the protected electrical element in the substation

A fault component network with segregated current fault component as shown in Fig. 1, it can be obtained:

$$\Delta \dot{U}_{f0} = \frac{\Delta \dot{E}_f Z_f}{Z_f + (Z_m + Z_{bm}) // (Z_{bn} + Z_n)} - \Delta \dot{E}_f \quad (1)$$

$$\Delta \dot{U}_m = \Delta \dot{U}_{f0} \frac{Z_m}{Z_m + Z_{bm}} \quad (2)$$

$$\Delta \dot{U}_n = \Delta \dot{U}_{f0} \frac{Z_n}{Z_n + Z_{bn}} \quad (3)$$

$$\Delta \dot{I}_m = \frac{\Delta \dot{U}_m}{Z_m} = \frac{\Delta \dot{U}_{f0}}{Z_m + Z_{hm}} \quad (4)$$

$$\Delta \dot{I}_n = \frac{\Delta \dot{U}_n}{Z_n} = \frac{\Delta \dot{U}_{f0}}{Z_n + Z_{bn}} \quad (5)$$

From equations (4) and (5), it can be concluded:

$$\arg(\Delta \dot{I}_m / \Delta \dot{I}_n) = \arg\left(\frac{Z_n + Z_{bn}}{Z_m + Z_{bm}}\right) \quad (6)$$

By analyzing the formulas (1), (4), (5) and (6), it can conclude that when the fault occurs in the protected electrical element area of the substation, the absolute magnitude of the fault component currents on both sides of the fault point is related to the transition resistance, and the relative magnitude is independent of the transition resistance. The phase angle difference between the fault component currents on both sides of the fault point depends only on the equivalent impedance characteristics, and is independent of the transition resistance and the system phase angle difference, and $\arg(\Delta \dot{I}_m / \Delta \dot{I}_n) \in (-90^\circ, 90^\circ)$ is close to 0° .

2.2 Analysis of segregated current fault component in the external fault of the protected electrical element in the substation

Similarly, when the fault occurs outside the protected electrical element area of the substation, the absolute magnitude of the fault component currents on both sides of the fault point is related to the transition resistance, and the relative magnitude is independent of the transition resistance. The phase angle difference between the fault component currents on both sides of the fault point is independent of the transition resistance and the system phase angle difference, and is only related to the impedance characteristics of the system itself, and $\arg(\Delta \dot{I}_m / \Delta \dot{I}_n) = \arg(-1) = 180^\circ$.

2.3 Principle of fault recognition in the substation area backup protection zone of intelligent substation with phase comparison of segregated current fault component

The direction of the current is directed to the positive direction of the current by the busbar pointing to the protected element. When the fault occurs in the protected electrical element area of the substation, the phase of the fault component currents on both sides of the electrical element are basically the same, close to 0° . When the fault occurs outside the protected electrical element area of the substation, the phase of the fault component currents on both sides of the electrical element are substantially opposite, close to 180° . Based on this fault feature, it is possible to clearly identify faulty electrical elements and normal operating electrical elements in the substation.

3. Fault recognition algorithms for substation area backup protection based on phase comparison of segregated current fault component

3.1 Quantification of phase characteristics of segregated current fault component

(1) In order to improve the distinction degree between faulty electrical elements and non-faulty electrical elements, the mathematical processing of the phase-invariant amplitude expansion of the fault component currents $\Delta i_m(t)$ and $\Delta i_n(t)$ on both sides of the electrical element is performed to make the fault currents equal. Assuming that the busbar points to the protected electrical element is the positive current direction, the fault component current is obtained by subtracting the power before the fault from the power after the fault.

$$\Delta i_{meq}(t) = \frac{(|\Delta i_m(t)| + |\Delta i_n(t)|) \times \Delta i_m(t)}{|\Delta i_m(t)|} \quad (7)$$

$$\Delta i_{neq}(t) = \frac{(|\Delta i_m(t)| + |\Delta i_n(t)|) \times \Delta i_n(t)}{|\Delta i_n(t)|} \quad (8)$$

(2) The conclusions drawn from the analysis in Section 2.3 are as follows. When the fault occurs in the protected electrical element area of the substation, the phase of the fault component currents on both sides of the electrical element are basically the same, close to 0° . When the fault occurs outside the protected electrical element area of the substation, the phase of the fault component currents on both sides of the electrical element are substantially opposite, close to 180° . Based on this characteristic, the fault current treated in (1) is further processed, and the comprehensive differential fault charge $\Delta Qd_{eq}(t)$ and the comprehensive braking fault charge $\Delta Qr_{eq}(t)$ are obtained.

$$\Delta Qd_{eq}(t) = \int_{t_1}^{t_2} |\Delta i_{meq}(t) + \Delta i_{neq}(t)| dt \quad (9)$$

$$\Delta Qr_{eq}(t) = \int_{t_1}^{t_2} |\Delta i_{meq}(t) - \Delta i_{neq}(t)| dt \quad (10)$$

(3) Quantification of phase comparison of segregated current fault component
Measuring degree of element fault:

$$\delta(t) = \frac{\Delta Qd_{eq}(t) - \Delta Qr_{eq}(t)}{\Delta Qd_{eq}(t) + \Delta Qr_{eq}(t)} \quad (11)$$

Formula (11) shows that when the fault occurs outside the protected electrical element area of the substation, the instantaneous currents of the equivalent currents $\Delta i_{meq}(t)$ and $\Delta i_{neq}(t)$ on both sides of the element are equal in magnitude and opposite in direction. In the time interval $[t_1, t_2]$, $\Delta Qd_{eq}(t) = 0$, $\Delta Qr_{eq}(t) \neq 0$, and the fault degree $\delta(t)$ is -1. When the fault occurs in the protected electrical element area of the substation, the instantaneous currents of the equivalent currents $\Delta i_{meq}(t)$ and $\Delta i_{neq}(t)$ on both sides of the element are equal in magnitude and in the same direction. In the time interval $[t_1, t_2]$, $\Delta Qd_{eq}(t) \neq 0$, $\Delta Qr_{eq}(t) = 0$, and the fault degree $\delta(t)$ is 1.

3.2 Calculation of fault measuring degree of all protected electrical elements in the substation

Before applying formulas, the multi-terminal element is first equivalent to the two-terminal element based on Kirchhoff laws. According to the formula of measuring degree of the element fault defined in Section 3.1, the fault measuring degree of all electrical elements in the station is calculated. According to the wiring diagram of a typical 220 kV substation and its adjacent substations, the fault component currents required for the fault measuring degree of the elements involved in the calculation are shown in Table 1.

Table 1. Fault component currents required by participating elements

Protected elements	Required fault component currents
BUS220-1	$\Delta i_2(t)$ 、 $\Delta i_{19}(t)$ 、 $\Delta i_{220}(t)$
BUS220-2	$\Delta i_4(t)$ 、 $\Delta i_{20}(t)$ 、 $\Delta i_{220}(t)$
BUS110-1	$\Delta i_6(t)$ 、 $\Delta i_8(t)$ 、 $\Delta i_{21}(t)$ 、 $\Delta i_{110}(t)$
BUS110-2	$\Delta i_{10}(t)$ 、 $\Delta i_{11}(t)$ 、 $\Delta i_{22}(t)$ 、 $\Delta i_{110}(t)$
BUS35-1	$\Delta i_{14}(t)$ 、 $\Delta i_{17}(t)$ 、 $\Delta i_{23}(t)$ 、 $\Delta i_{35}(t)$
BUS35-2	$\Delta i_{15}(t)$ 、 $\Delta i_{18}(t)$ 、 $\Delta i_{24}(t)$ 、 $\Delta i_{35}(t)$
T1	$\Delta i_{19}(t)$ 、 $\Delta i_{21}(t)$ 、 $\Delta i_{23}(t)$
T2	$\Delta i_{20}(t)$ 、 $\Delta i_{22}(t)$ 、 $\Delta i_{24}(t)$

3.3 Fault recognition criterion in substation backup protection area with phase comparison of segregated current fault component

When the fault occurs in the protected electrical element area of the substation, measuring degree of the element fault $\delta(t)$ is 1, and when the fault occurs outside the protected electrical element area of the substation, $\delta(t)$ is -1. Based on this fault criterion, it is possible to clearly identify faulty electrical elements and normal operating electrical elements in the substation.

3.4 Algorithm flow for fault recognition in substation backup protection area with phase comparison of segregated current fault component

According to the principle and algorithm of fault recognition in substation backup protection area based on phase comparison of segregated current fault component, the flow of fault recognition is obtained. The flow chart of the algorithm is shown in Figure 3.

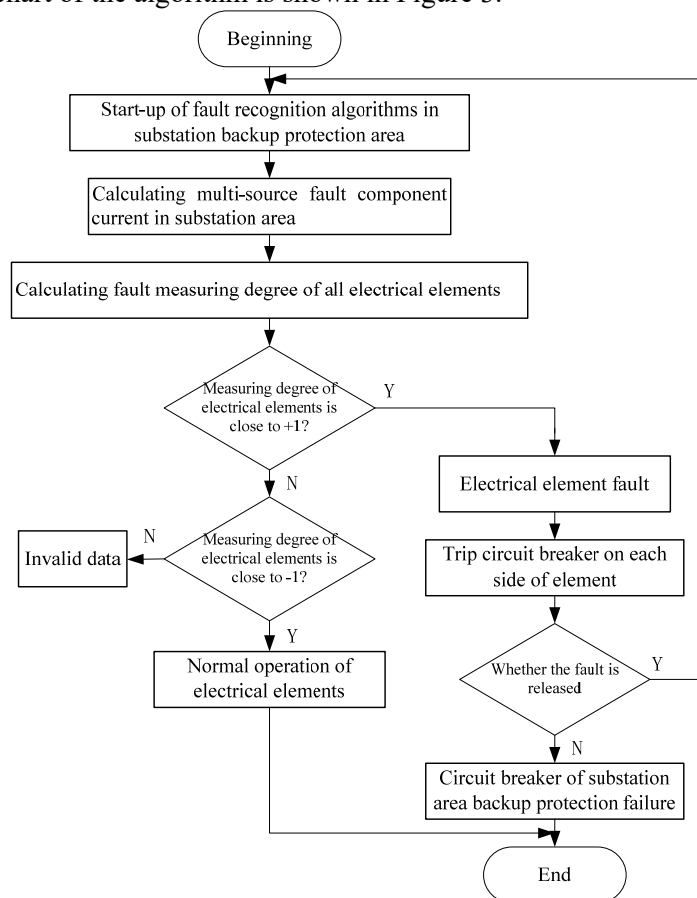


Figure 3. Flow chart of fault recognition algorithm in substation backup protection area of phase comparison of segregated current fault component

4. Simulation

Based on the PSCAD/EMTDC electromagnetic transient simulation software, a typical 220 kV substation model is built, as shown in Figure 4. The different fault conditions are analyzed respectively, and the validity and feasibility of the fault recognition algorithm in the substation backup protection area of phase comparison of segregated current fault component are verified. The sampling frequency was 1MHz, and the time window was 1/4 cycle after the fault, that is, 20 sample values are used to calculate the measuring degree of the element fault in the substation. The simulation system was put into operation at 0 seconds, and the fault was put in 0.2 seconds, and the fault duration was 0.1 seconds.

The equivalent voltage source represented by Thevenin's theorem can be used in adjacent substations to arbitrarily adjust the voltage amplitude and angle of the equivalent power source and then simulate different operation states. Frequency-dependent line model of distributed parameters was used for transmission line. The wiring form of the transformer is Y/Y Δ -12-11, $S_N = 180\text{MVA}$, $U_{1N}/U_{2N}/U_{3N} = 220/110/35\text{kV}$. The neutral point of the high and medium voltage sides was grounded. The constant power model was adopted in the middle and low voltage sides of the substation.

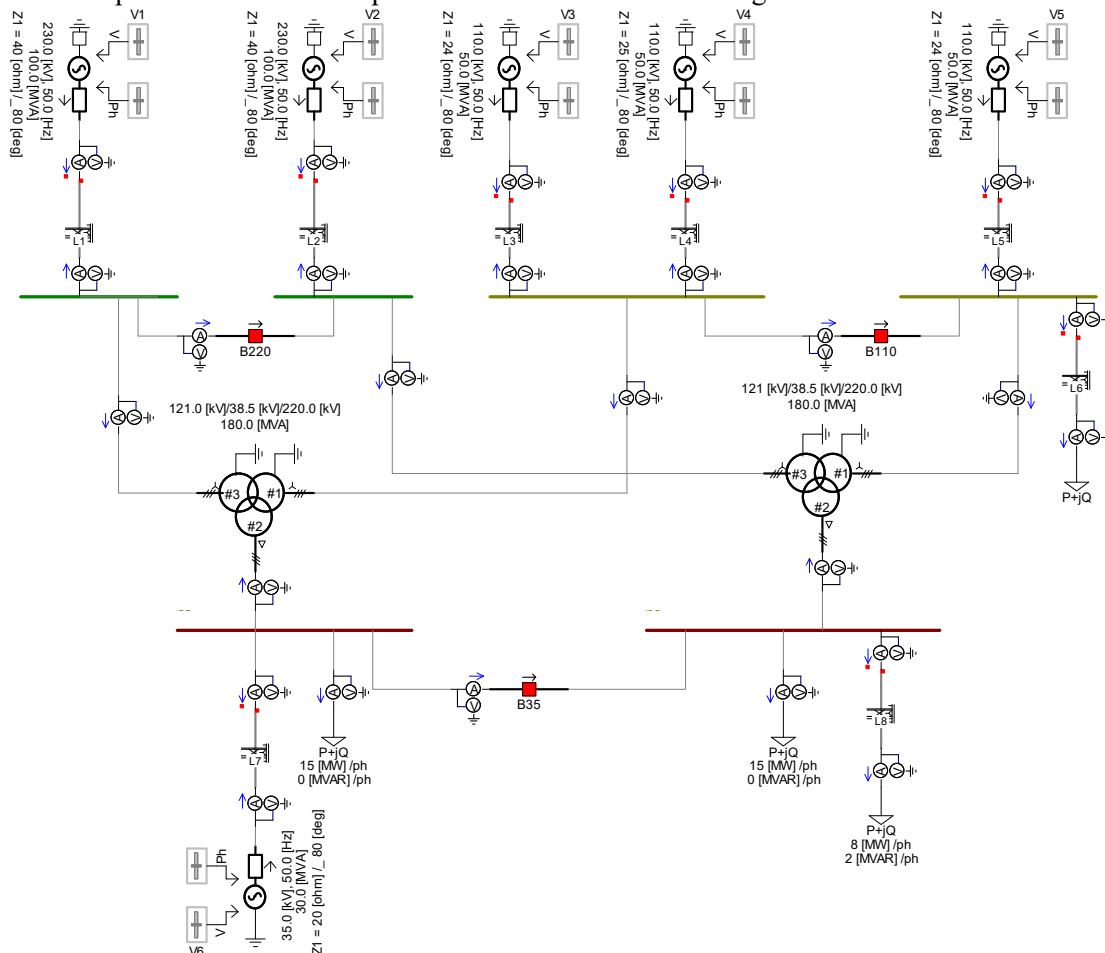


Figure 4. Typical PSCAD simulation model of 220 kV intelligent substation

4.1 Examples of fault element recognition with different fault types

In order to verify that the fault recognition algorithm in the substation backup protection area of the phase comparison of segregated current fault component can meet different fault types, the transition resistance $R_g = 100\Omega$ was set and only for the same protected electrical element, such as the BUS220-1 bus. Different types of faults were set in PSCAD to verify that the protection algorithm was not affected by the fault type. Fault measuring degree of each element, as shown in Table 2.

Table 2. Fault measuring degree of all electrical elements

Fault measuring degree of the protected element (δ_i)	Two-phase ungrounded	Two-phase grounded	Single-phase ground	Three-phase short-circuit
①T1	-1	-1	-1	-0.9674
②T2	-0.8643	-0.8472	-0.9920	-0.9239

③BUS220-1	+1	+0.9691	+1	+1
④BUS220-2	-1	-1	-1	-1
⑤BUS110-1	-1	-1	-1	-1
⑥BUS110-2	-1	-1	-1	-1
⑦BUS35-1	-1	-1	-1	-1
⑧BUS35-2	-1	-1	-1	-1

It can be clearly compared that fault measuring degree of elements only the bus BUS220-1 is close to +1, and the fault measuring degree of other elements is close to -1. Therefore, it can be recognized that only the bus BUS220-1 is faulty, and other electrical elements in the substation are operating normally. The simulation results of different fault types show that the algorithm is not affected by the fault type.

4.2 Examples of fault element recognition with different transition resistances

In order to verify that the fault recognition algorithm based on energy relative entropy was not affected by transition resistance in the substation backup protection area, for the T2 transformer, two-phase grounded fault was set in PSCAD, and the grounding resistances $R_g = 0\Omega$, $R_g = 100\Omega$ and $R_g = 800\Omega$ were set respectively. Different transition resistances were set in PSCAD to verify that the protection algorithm was not affected by the transition resistance. Fault measuring degree of each element, as shown in Table 3.

Table 3. Fault measuring degree of all electrical elements

Energy relative entropy of the protected element (W_i)	Transition resistance (0Ω)	Transition resistance (100Ω)	Transition resistance (800Ω)
①T1	-1	-0.7003	0.0140
②T2	+1	+1	+1
③BUS220-1	-1	-1	-1
④BUS220-2	-1	-1	-1
⑤BUS110-1	-1	-1	-1
⑥BUS110-2	-1	-1	-1
⑦BUS35-1	-1	-1	-1
⑧BUS35-2	-1	-1	-1

It can be clearly compared that the fault measuring degree of elements only the transformer T2 is +1, and the fault measuring degree of other elements are all -1. Therefore, it can be recognized that only the transformer T2 is faulty, and other electrical elements in the substation are operating normally. The simulation results of different fault types show that the algorithm is not affected by the transition resistance.

5. Conclusions

In this paper, the substation area backup protection fault recognition algorithm for phase comparison of segregated current fault component was studied. According to the fault component current characteristics in and out of the protected electrical elements, the fault recognition principle of substation area backup protection based on phase comparison of segregated current fault component

was proposed. Based on this principle, a fault identification method for substation area backup protection was proposed with phase comparison of segregated current fault component, which can realize the fast and accurate location of fault elements in the substation. Through the simulation of different fault types, different fault locations and different transition resistors, it is shown that this protection algorithm is not affected by fault types and transition resistance, and can identify different fault types of electrical elements, which verifies the feasibility and correctness of this protection algorithm. At the same time, the protection algorithm can effectively solve the problems of traditional backup protection in setting and coordination, operation time limit, safety and stability, and improve the performance of backup protection.

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