A Fast Bus Bar Protection Based on Fault Superimposed Current Polarity Comparison

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Abstract. In order to avoid problems caused by data synchronization of distributed bus bar protection and current transformer (CT) transient saturation, a novel fast bus bar protection was proposed based on fault superimposed current polarity comparison. The bus protection takes the pre-fault voltage and pre-fault current as the new reference for polarity comparison, and it utilizes the relationship between the pre-fault current and superimposed current to identify the fault direction. For internal faults at bus bar, the polarities of the branches connected to the faulted bus bar are identical, for external faults, the polarities are not exactly same. The time window length of fast bus bar protection is very short, and the relay is also immune to the CT transient saturation. The theoretical analysis and PSCAD/EMTDC simulation tests show that the bus protection operates reliably and rapidly, and that its performance is immune to the influences of various fault types, fault path resistance and fault inception angle.

Introduction

With the continuous deepening of smart grid construction in China, the intellectualization transformation of traditional substations has been comprehensively promoted, intellectualized electronic transformers are gradually replacing traditional electromagnetic transformers due to their advantages of miniaturization, digitalization and good transient transmission characteristics. But for now, the operation of power grid is still facing the situation of the coexistence of the traditional electromagnetic transformer and the intelligent electronic transformer. Because of the electromagnetic transformer and electronic transformer have great differences in working principle, transient characteristic, signal transmission and processing, it is very difficult to be compatible of the two types of transformer using in differential protection, which restricts the development of intelligent power system, digitalization and automation in a certain develop[1-4].

Bus differential protection is one of the differential protection which widely used in power system as the main protection of equipment and line. Bus bar is the hub of line connection in power grid. Generators, transformers, transmission lines, power supply lines and other devices in power plants and substations play a role through buses. If the bus bar fault can not be removed in time, it will cause damage to the power equipment, destroy the stable operation of the power system, and even cause catastrophic consequences. Therefore, it is particularly important to be equipped with fast, sensitive, high reliability and selective bus protection in high voltage power grid. The widely used bus protection at present is distributed current differential protection based on the power frequency, which is composed of two parts: central unit (CU) and bay unit (BU). Due to the centralized processing of the traditional bus differential protection, secondary current all CTs need pass through the cable into the same protective device, which not only consumes a large amount of cable, but also makes the connection of secondary side becomes very complicated, brought many difficulties for operation and maintenance on site. The secondary side connection of the distributed bus differential protection will be greatly simplified, thus improving the reliability of the system and reducing the cost of operation and maintenance [5,6]. However, the synchronous of data sampling is a necessary condition for current differential protection. Moreover, unlike line current
differential protection, all sampled data from BU are transmitted through the same transmission channel, so all data have the same transmission delay.

In addition, with the expansion of the grid size and the increasing of the voltage and the transmission power, there will be a serious transient saturation problem in the traditional electromagnetic transformer when the short-circuit fault occurs, the fastest action time of the current differential bus protection is about 1 cycle and the ability of anti-saturation is poor. The difference between time difference method [7-9], harmonic restraining method [10] and other methods is only that the identification method of CT saturation is slightly different, which cannot really achieve the duality of bus bar protection principle. And the action time of the harmonic restraining method is not less than 20ms, which cannot meet the requirements of the speediness of the ultra-high voltage power grid. Based on the identification of the model parameters and the parameter dispersion, the model parameter identification method [11] can accurately predict the internal and external faults of the bus bar and the CT saturation of the external faults. This principle does not need to set the CT saturation detection element and the motion speed is faster, but the sensitivity of the internal fault is reduced.

At present, the transient current comparative directional protection [12] of HV transmission lines is relatively perfect in theory and mature in technology. On the basis of this, this article develops a current polarity comparison fast bus protection based on fault component. By doing phase calculation using the current information collected independently by the protection unit on each line and send the logical signal to the central unit for processing, it solves the problem that data acquisition needs hardware synchronization between BUs and CT and ECT data can't cooperate effectively in existing distributed bus protection. At the same time, the proposed method using short data window that reduces the affection of CT saturation, and the motion speed is fast. The sampling frequency is low, which is easy to be realized in engineering. The theoretical analysis and PSCAD/EMTDC simulation tests show that the bus protection operates reliably and rapidly, and that its performance is immune to the influences of various fault types, fault path resistance and fault inception angle.

**Principle of Bus Bar Protection**

**Fault Feature Analysis**

Figure 1 shows a schematic diagram of a substation bus bar fault. There are 3 lines on the bus M, respectively $L_1$, $L_2$ and $L_3$. $R_1$, $R_2$ and $R_3$ are local protection units installed at the outlet of the bus. The current direction is from the bus to the line and the power flow is judged according to the voltage and current phase of each line direction element one cycle before the fault.

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![Figure 1. Schematic diagram of bus fault in substation.](image)

When a fault occurs on a bus bar, its fault attachment network is shown as shown in Figure 2. Study line $L_1$, in its protection unit $R_1$ reverse direction (power flow) $f$ point, that is, when the bus fault occurs, the power flow before the fault of Figure 2 can be obtained:

$$u_f \times i_1 > 0$$

where $u_f$ is pre-fault voltage of point $f$ , $i_1$ is the pre-fault current flowing through the protective installation.
It is known from the superposition theorem of Figure 2:

\[ u_f = -\Delta u_f \]  \hspace{1cm} (2)

where \( \Delta u_f \) is the fault component voltage at the fault point \( f \).

In the case of reverse direction fault, it is known from the principle of the traditional traveling wave polarity comparison direction element\textsuperscript{[12]}:

\[ \Delta u_f \times \Delta i > 0 \]  \hspace{1cm} (3)

where \( \Delta i \) is the difference between the current flowing through the protective installation before and after the fault, that is, the fault component current of this point.

From (1) - (3) can get the polarity relationship between the pre-fault current and the frequency current component of the fault when the reverse direction fault occurs:

\[ i \times \Delta i < 0 \]  \hspace{1cm} (4)

For bus bar fault, the current of each lines are opposite to the fault component before fault. Figure 3 shows a schematic diagram of a bus bar outlet fault, the power flow is judged according to the voltage and current phase of each line direction element one cycle before the fault.

Figure 3. Schematic diagram of the substation bus external fault.

When an external bus fault occurs, the fault attached network is shown as shown in Figure 4. Study line \( l_1 \), in its protection unit \( R \) forward direction (power flow) \( F \) point, that is, when the external bus fault occurs, the power flow before the fault of Figure 4 can be obtained:

\[ u_f \times i > 0 \]  \hspace{1cm} (5)

where \( u_f \) is pre-fault voltage of point \( F \), \( i \) is the pre-fault current flowing through the protective installation.

Figure 4. Fault attached network for external bus fault.

It is known from the superposition theorem of Figure 4:
where \( \Delta u_f \) is the fault component voltage at the fault point \( F \).

In the case of forward direction fault, it is known from the principle of the traditional traveling wave polarity comparison direction element\([12]\):

\[
\Delta u_f \times \Delta i_i < 0
\]

where \( \Delta i_i \) is the fault component current of this point.

From (5) - (7) can get the polarity relationship between the pre-fault current and the frequency current component of the fault when the forward direction fault occurs:

\[
i_i \times \Delta i_i > 0
\]

For the faulty line, the polarity of the current and fault component current is the same at the point of protection installation. For other non-fault lines, the polarity of the current is opposite with the fault component current at the point of protection installation.

The current polarity criterion is obtained based on single-phase system. When it is applied to three-phase transmission line, in order to avoid the influence of interphase coupling, this paper uses phase mode transformation to decouple the mutually coupled three-phase systems into independent single-phase systems. Considering that the existing Clarke and other transformation matrixes do not reflect all kinds of fault types, the new phase mode transformation proposed by reference [13] is shown in the following expressions:

\[
\begin{bmatrix}
    f_a \\
    f_b \\
    f_c
\end{bmatrix}
= \begin{bmatrix}
    1 & 1 & 1 \\
    1 & 2 & -3 \\
    1 & -3 & 2
\end{bmatrix}
\begin{bmatrix}
    f_a \\
    f_b \\
    f_c
\end{bmatrix}
\]

Criterion for Bus Bar Protection

The algorithm process of the fast bus bar protection based on fault superimposed current polarity comparison is shown in Figure 5.

**Figure 5.** The algorithm process of the fast bus bar protection based on fault superimposed current polarity comparison.
1) Time domain signal extraction with power frequency band

After the start of each bus line protection elements, get the fault component in a short period of time after the fault and the steady state current wave corresponding to the previous cycle at the point of protection installation, and sampling frequency is 5kHz. The fault component of phase mode transformation is used to extract the power frequency band time domain signal. The fault current is mainly composed of power frequency components, so the multi-resolution analysis of the fault components is carried out on the basis of wavelet transform, and it is decomposed into sub band space. When the sampling frequency is 5kHz, the fifth layer approximate coefficient contains the power frequency component (0~78.125Hz). The wavelet decomposition approximation coefficient of the layer is reconstructed, and the time domain signal components corresponding to the frequency band of the work frequency are \( i_{RS} \) and \( \Delta i_{RS} \).

2) Protection criterion

After extracting the time domain signal components \( i_{RS} \) and \( \Delta i_{RS} \), the 3ms data window is selected and the polarity of the two angle \( \theta \) is obtained, as shown in formula (10). Considering the sensitivity of the directional element in the forward and reverse direction, the threshold value of the polarity comparison is \( \theta_0 = 90^\circ \), when the power direction is positive, if \( \theta > \theta_0 \), judge it as forward fault, \( P = 1 \); if \( \theta < \theta_0 \), judge it as reverse fault, \( P = 0 \). Formula (11) is used to judge whether it is a bus bar fault. Considering the possible existence of bad data, \( N \) times are calculated in the data window, and if there are \( S \) times calculation to satisfy the criterion, the polarity state is determined, \( S/N \geq 0.8 \).

\[
\theta(k) = \cos^{-1}\left(\frac{\sum_{j=1}^{N}[i_{n_1}(j-N)\Delta i_{n_1}(j)]}{\sqrt{\sum_{j=1}^{N}i_{n_1}(j-N)^2} \sqrt{\sum_{j=1}^{N}\Delta i_{n_1}(j)^2}}\right) \tag{10}
\]

\[
G_m = \prod_{i=1}^{n} P_i \tag{11}
\]

3) The distributed system structure of bus bar protection

Based on the above protection criteria, the polarity criterion of each outlet protection is aggregated by the state information quantity. Considering that the outlet sudden variables start and the weak feeder lines may fail to start, it can delay the amount of 2~3ms receiving state information. \( G_m = 1 \), judge it as bus bar fault, \( G_m = 0 \), judge it as outlet fault. Polarity criterion solves the problem of hardware synchronization in data acquisition between BU in existing distributed bus bar protection, making each line logical judgement independently, and provides a basis for the mixed use of ECT and CT.

**PSCAD Simulation Research**

Simulation model of dual bus parallel operation in PSCAD/EMTDC, as shown in Figure 6. \( E_1, E_2 \) are generators, \( T_1, T_2 \) are transformers, \( S = 400MVA \), voltage is 242/24kV, connection type is \( Y/\Delta-11 \), short circuit capacity of power system is 300MVA, \( X/R = 10 \). The protection element is installed at the outlet of each line, and the sampling frequency is 5kHz. Considering the saturation of CT, the transformers use the JA model.
Fault Simulation and Analysis

1) Bus bar fault. The simulation model according to figure 6, an impedance short-circuit grounding of the A phase of the bus II occurs at 2s, duration is 80ms, the simulation time is 3s. Figure 7 is the current waveform of each line. Figure 8 is the time domain result of the polarity judgment at the typical protection installation.

Figure 6. 220kV bus simulation model.

Figure 7. Current waveform of each outlet of 220kV bus fault.

(a). Time domain characteristics of outlet In1 current polarity

(b). Time domain characteristics of outlet In2 current polarity

Figure 8. Time domain characteristics of typical outlet current polarity.
The result of the line mode current polarity and the protection criterion obtained by the formula (10) and (11) can be correctly identified as the bus bar fault.

2) Bus bar external fault. An impedance grounding of the A phase is set at 2s, duration is 80ms, the simulation time is 3s, and the simulation model is shown as Figure 9. Figure 10 is the current waveform of each line. Figure 11 is the time domain result of the polarity judgment at the typical protection installation.

![Figure 9. Schematic diagram of 220kV bus external fault.](image)

![Figure 10. Current waveform of each outlet of 220kV bus external fault.](image)

(a). Time domain characteristics of outlet In1 current polarity

(b). Time domain characteristics of outlet In2 current polarity

![Figure 11. Time domain characteristics of typical outlet current polarity.](image)

The result of the line mode current polarity and the protection criterion obtained by the formula (10) and (11) can be correctly identified as the bus bar external fault.
**Protection Action Speed and Performance Analysis**

The computation of fast polarity comparison bus protection based on current fault components is mainly reflected in three aspects: phase mode transformation, wavelet decomposition and reconstruction, and angle calculation. The multiplication times of the twice phase mode transformation and the angle calculation are about 80 times. The multiplication times required for the wavelet decomposition and reconstruction are related to the signal length $M$ and the filter length $L$. At present, the performance of the processor is improved quickly. The computing speed of the traditional single chip computer is about 0.2MIPS, which is about 125~250 times per millisecond. With the support of the hardware circuit, the DSP can reach 20~40MIPS, which is about 2E5~4E5 times per millisecond. FPGA is faster for the matrix operation, and the peak calculation speed can reach 1.5E6 times per millisecond. Considering the amount of calculation in this paper, if DSP plate is used, it can be controlled within 0.5ms.

The polarity comparison criterion uses the angle to characterize the polarity and is independent of the amplitude, so it can be better adapted to the condition of the initial angle of the small fault and the high resistance fault. The polarity criterion uses state information to solve the problem of hardware synchronization of data acquisition between BU in existing distributed bus protection. Because of reconstitution of the power frequency of the fault current only, this method can effectively filter high frequency fault information and high frequency noise in reality, so polarity comparison criterion has a certain ability of noise immunity.

**Conclusion**

In this paper, a fast bus bar protection based on fault superimposed current polarity comparison is proposed. The proposed method using short data window that reduces the affection of CT saturation, and the motion speed is fast. The sampling frequency is low, which is easy to be realized in engineering. Using statement information solves the problem of hardware synchronization in data acquisition between BU in existing distributed bus bar protection, making each line logical judgement independently, and provides a basis for the mixed use of ECT and CT.

**Reference**


