Principle of Distributed Bus Protection Based on Directional Impedance Component Comparison

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Abstract. Distributed bus protection is one of the main tasks of smart substation construction to improve the secondary system because it is economical, simple, easy to layout, and easy to realize double. This paper mainly considers that distributed current differential protection is limited by high precision synchronization and high bandwidth and a distributed bus protection based on the directional impedance element comparison principle is proposed. The bus impedance protection constructed by reverse current calculation is proposed, which the impedance protection with positive sequence polarization and the impedance protection with memory polarization are the main components. Further considering the influence of system oscillation, the power frequency variable distance protection is introduced to form a distributed bus protection system, and the setting and time setting principles are given. The principle of the protection system is simple and the action is reliable. The effectiveness of the protection system is verified based on PSCAD simulation software.

Keywords: distributed bus protection; impedance protection; direction comparison; system oscillation

1. Introduction

As a key component of the smart grid, digital substation has developed rapidly in China and abroad. The busbar in the substation undertakes the important task of current convergence and distribution, and its reliability plays a vital role in the safe and stable operation of a power system [1-2]. Traditional microcomputer busbar protection mainly adopts the centralized protection mode. The secondary wiring is complex and costly. The refuse operation of busbar protection may cause damage to power equipment and the disintegration of the system, and the misoperation of busbar protection will cause large-scale blackout.

With the rapid improvement of computer and communication technology, distributed busbar protection has become the trend of future development due to its simple structure, local layout, and easy realization of double configuration [3-4]. The principle of current differential protection is simple and reliable, which is the main protection principle of traditional microcomputer busbar protection and distributed bus protection. Cross-interval sampling value synchronization is one of the difficulties in the process bus communication of digital substations. There are mainly two solutions to synchronization issues. One is to improve the reliability of the synchronous clock by improving the synchronization technology. References [5-6] propose to use the difference between the time benchmarks of the busbar...
protection central control unit (CU) and the busbar protection local control unit (BU) to achieve sampling synchronization. The other is to use a new principle and method of distributed busbar protection without data synchronization. References [7] propose a distributed busbar protection based on the principle of traveling wave direction. The principle requires a small amount of information, and the data at each interval need not be synchronized. However, there is no transient traveling wave when fault occurs at the voltage zero-crossing, therefore the protection principle has defects.

To solve the problem of distributed busbar protection affected by data synchronization, this paper proposes a distributed busbar protection principle based on directional impedance element comparison. The current information and cascade bus voltage independently collected by the protection unit on each line is used to determine the fault direction by using the directional impedance element, and then the fault direction of each line on the busbar is comprehensively compared to judge the internal and external fault of the busbar. This principle does not require interval data synchronization and is less affected by data transmission delay. At the same time it can quickly and reliably judge the fault direction, less affected by the system oscillation. The validity and feasibility of the principle are verified by PSCAD/EMTP simulation.

2. The Structure of Distributed Busbar Protection
Distributed busbar protection schemes can be roughly divided into two categories. One is bus-type distributed busbar protection, as shown in Figure 1. Each bay-unit communicates only with the central-unit, transmits information to and receives information and commands from the central-unit, and the protection function is accomplished by both the central-unit and the bay-unit. The other is ring-type distributed bus protection, as shown in Figure 2. The bay-units connect in series through a ring communication network, receiving information from all other bay-units and transferring the collected information to all other bay-units. Each bay-unit uses this information to complete busbar protection function independently.

Figure 1. Bus-type distributed busbar protection  Figure 2. Ring-type distributed bus protection.

Compared with the bus-type distributed bus protection, the ring-type distributed bus protection is more in line with the technical characteristics of the new generation of smart substation. In addition, when the local control unit of the busbar protection is judged as a busbar fault, it only disconnects the corresponding circuit from the busbar without affecting other circuits. Therefore, even if a busbar protection unit of the ring-network distributed busbar protection is misjudged and jumped by mistake, it is only to jump out of the corresponding circuit, without causing the power outage of the entire busbar.

At present, most busbar protections are centralized current differential protections. After sample value has been summarized in the central unit, central unit executes calculation and sends commands. Distributed busbar protection uses current differential protection in the same principle as centralized protection. This requires each merge unit to accept sample values sent by other units and perform a differential calculation to determine whether the failure occurred, so it is necessary to achieve high consistency in communication and synchronization. However, in the case of more intervals, the real-time data of busbar differential protection is required and the amount of data communication is larger. Therefore, considering the technical problems of current differential protection in distributed protection, this paper proposes a distributed busbar protection based on directional impedance element comparison principle.
3. The Principle of Busbar Protection

3.1. The Analysis of Fault Characteristics

Based on the distance protection, we can get (1), the working voltage $\hat{U}_m$ is usually expressed as the linear combination of the measured voltage $\hat{U}_m$ and the measured current $\hat{I}_m$ at the protection installation,

$$\hat{U}_m = \hat{U}_m - \hat{I}_m Z_{set} \tag{1}$$

In (1), $Z_{set}$ is the setting impedance, which corresponds to the line impedance from the protection installation to the set point.

In the traditional line distance protection, different reference voltage $\hat{U}_ref$ and different action boundary $\beta_1$ and $\beta_2$ are selected first. Based on the phase difference between $\hat{U}_m$ and $\hat{U}_ref$ under different fault conditions of inside and outside the area, the location of the fault point can be distinguished, and the line forward protection can be realized. The size of the protection range is determined by the protection setting impedance $Z_{set}$.

The busbar is located at the back of the line protection installation, which is the opposite position of the line. Referring to the principle of traditional line impedance protection, busbar impedance protection can be constructed by current reverse calculation. The protection schematic diagram is shown in figure 3. When a transmission line fault occurs, the measured impedance at the installation will only fall into their respective line impedance protection zone. When the busbar fault occurs, the reverse impedance component of each line will act, as shown in figure 3, the overlapping area is the busbar impedance protection area.

![Diagram](image_url)

**Figure 3.** Schematic diagram of busbar impedance protection.

3.1.1. Z3/Z4 Protection Principle. The busbar is a confluence element, and the voltage transformers are generally installed on the busbar or at the line outlet. When the busbar fault occurs, the voltage dead zone generally occurs. Therefore, when considering the principle of busbar impedance protection, it is necessary to select a variety of reference voltages according to different fault types to deal with the voltage dead zone issues. According to the line protection configuration, this paper selects the impedance protection based on positive sequence voltage polarization and voltage memory polarization as the main components. Considering the characteristics of impedance protection may misoperate when the system oscillates, the busbar impedance protection is equipped with power frequency variation distance protection at the same time. The voltage component of the busbar impedance protection takes the voltage of the bus voltage transformer, and the current takes the
current of the current transformer of each line, and the current takes the reverse calculation in impedance calculation. The action criterion of the reverse impedance element is shown in Table 1.

Table 1. Action Criterion of Anti-directional Impedance Element.

| Protection configuration | Wiring mode               | Operation Criterion                                      |
|-------------------------|---------------------------|----------------------------------------------------------|
| Positive sequence voltage polarization | Grounding distance        | $-90^\circ \leq \arg \left( \frac{U - (-I + K \times 3I)}{U_{m}} \right) \leq 90^\circ $ |
|                         | Phase-to-phase distance   | $-90^\circ \leq \arg \left( \frac{U_{m} - (-I_{m})Z_{m}}{U_{m}} \right) \leq 90^\circ $ |
| Memory voltage polarization | Grounding distance       | $-90^\circ \leq \arg \left( \frac{U_{m} - (-I_{m})Z_{m}}{U_{m}} \right) \leq 90^\circ $ |
|                         | Phase-to-phase distance   | $-90^\circ \leq \arg \left( \frac{U_{m} - (-I_{m})Z_{m}}{U_{m}} \right) \leq 90^\circ $ |
| Power frequency variation | Grounding / Phase-to-phase | $|\Delta U - (\Delta I)Z_{m}| \geq U_{th}^{(m)}$ |

3.1.2. Protection Setting Calculation. Busbar fault is mainly phase-to-phase fault, for grounding fault is line to insulator or earth discharge short circuit, generally will not happen high resistance grounding fault. Therefore, only the arc resistance is considered in the calculation of the setting value when the busbar fault occurs. It is recommended that the resistance is not greater than 25 $\Omega$ under different voltage levels, and then the impedance value in the direction of the line impedance angle is calculated according to the characteristics of the direction circle. The protection setting value can be obtained as (2), $\varphi$ is the line impedance angle.

$$Z_{m} = 25 / \cos \varphi \quad (2)$$

3.1.3. Time Setting Calculation. The busbar is a node of the transmission system, and the protection range includes the circuit breaker area. Compared with the system impedance, the bus impedance is very small. When the system oscillates, the possibility of the oscillation center falling on the bus node is very small. Even if it falls into the busbar protection area, as shown in Figure 3, when the system oscillates, the time of oscillation trajectory passing through the overlapping area is related to the overlapping range. It can be seen from Figure 3 that the oscillation impedance trajectory passes through the maximum area of the busbar impedance protection. The angle formed by the two points of the regional boundary and the protection installation point is $\alpha$ and the oscillation period is $T$, the time of the impedance trajectory staying in the busbar protection area can be obtained as (3):

$$t_{\alpha} = \frac{\alpha}{360^\circ} \times T \quad (3)$$

In order to avoid the influence of system oscillation on bus impedance protection, it is only necessary to set the setting time greater than $t_{\alpha}$, so as to ensure the reliability of the protection criterion.

Therefore, according to the above analysis of the inverse impedance element bus protection principle, it can be known that when the busbar fault occurs, the criterion for the action of the reverse impedance element of the distance protection is met, and the busbar protection control unit on each line will act. When the fault occurs on line, the line does not meet the action criterion of the anti-directional impedance element, so at least one line does not act.
3.2. Action Criterion of Busbar Protection

The distributed busbar protection adopts the ring network busbar protection structure, and each line interval needs to form the communication of the ring network. To prevent the data transmission error caused by communication, the above three directional impedance components are applied to the protection units of each line interval in this paper. These three criteria are not affected by each other. Even if bad data appear in the communication process, this method can also ensure certain fault tolerance.

Firstly, through the measured voltage and current obtained at the protection installation, a point difference is carried out to filter the decaying DC component. It can avoid the wrong phase comparison caused by the DC component, and cause the incorrect operation of the anti-directional impedance component.

The fundamental wave phasor of voltage and current is extracted by the Fourier algorithm, and the power frequency variation of voltage and current is calculated by the difference method. Then the fault direction of each line is judged by three kinds of anti-directional impedance components in each line interval protection unit. If the action criterion of the anti-directional impedance element is satisfied, the anti-directional fault is judged, and \( P_i = 1 \). If not satisfied, it is judged to be a positive fault, and \( P_i = 0 \). Then through (4) to determine whether the busbar fault occurs.

\[
G_M = \prod_{i=1}^{n} P_i \tag{4}
\]

Based on the above protection criterion, the direction criterion of each line protection unit is aggregated with state information. If \( G_M = 1 \), it is judged as a busbar fault. If \( G_M = 0 \), it is judged as line fault. The existing distributed busbar protection requires strict hardware synchronization for data acquisition of local control units of different busbar protections, and the direction comparison criterion proposed in this paper can effectively solve this problem.

4. Simulation Verification

The simulation model is built in PSCAD, and the 500kV bus simulation model is used as shown in figure 4. The S1 side system parameter is \( Z_{s1} = 1.0515 + j43.1749\Omega \), \( Z_{s1} = 0.5998 + j29.0911\Omega \). The S2 side system parameter is \( Z_{s2} = 2.5998 + j4.4918\Omega \), \( Z_{s2} = 2.0 + j3.7469\Omega \). System parameters on S3 side are the same as those on S2 side. The line parameters are \( Z_i = (0.0195 + j0.2779)\Omega / \text{km} \), \( Z_i = (0.1699 + j0.7131)\Omega / \text{km} \).

The length of transmission line \( L_1 \) is 20 km, the length of transmission line \( L_2 \) is 40 km, and the length of transmission line \( L_3 \) is 20 km.

![Figure 4. 500 kV Busbar protection simulation model.](image)

The following studies are conducted on the identification of busbar protection when fault F occurs on the busbar, fault \( F_1 \) occurs at the outlet of transmission line L1. And the performance of the bus protection under different fault types, fault distances, and system oscillation conditions are investigated. Tables 2-3 list part of the results in a large number of simulation experiments. DP1 and DP2 represent the anti-directional impedance element with positive sequence voltage and memory voltage as the
reference voltage, DP3 represents the anti-directional impedance element with power frequency variation. P1, P2 and P3 represent the discrimination results of the local control unit of busbar protection on lines L1, L2 and L3 respectively.

4.1. Internal Bus Fault
Reference to figure 4, busbar fault occurs in 1s and lasts 150ms. The action of three kinds of anti-directional protection elements of each line in the case of phase A grounding fault is shown in figure 5. Limited to the length of the article, other fault types of action as shown in table 2. Through the protection action of three lines, the criterion can correctly identify the internal busbar fault. Also, the criterion can still correctly identify the internal busbar fault under the condition of system oscillation.

![Figure 5](image_url)

**Figure 5.** Action of each line when bus A is connected to ground.

| Table 2. Discrimination Results of Busbar Fault. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| F               | AG element      | BG element      | CG element      | AB element      | BC element      | CA element      | GM   |
|                 | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        |      |
| AG              | 1/1/1           | 1/1/1           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0 |
| BG              | 0/0/0           | 0/0/0           | 1/1/1           | 1/1/1           | 1/1/1           | 1/1/1           | 0/0/0 |
| CG              | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0 |
| AB              | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0 |
| BC              | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 1/1/1           | 0/0/0 |
| CA              | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 1/1/1 |
| ABG             | 1/1/1           | 1/1/1           | 1/1/1           | 1/1/1           | 0/0/0           | 0/0/0           | 0/0/0 |
| BCG             | 0/0/0           | 0/0/0           | 1/1/1           | 1/1/1           | 1/1/1           | 0/0/0           | 0/0/0 |
| CAG             | 1/1/1           | 1/1/1           | 0/0/0           | 0/0/0           | 1/1/1           | 0/0/0           | 0/0/0 |
| ABCG            | 1/1/1           | 1/1/1           | 1/1/1           | 1/1/1           | 1/1/1           | 1/1/1           | 1/1/1 |

4.2. Line Fault
The simulation model refers to figure 4, #1 line fault occurs in 1s and lasts 150 ms. Limited to the length of the article, the actions of other fault types are shown in table 3. By judging the protection actions of three lines, the criterion can correctly identify the external busbar fault.

| Table 3. Discriminant Results of F1 Fault. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| F               | AG element      | BG element      | CG element      | AB element      | BC element      | CA element      | GM   |
|                 | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        | P1/P2/P3        |      |
| AG              | 0/1/1           | 0/1/1           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0           | 0/0/0 |
| BG              | 0/0/0           | 0/0/0           | 0/1/1           | 0/1/1           | 0/0/0           | 0/0/0           | 0/0/0 |
All the simulation tests show that the distributed busbar protection based on the comparison of directional impedance components can correctly identify the internal and external fault of the busbar, and is not affected by the fault type, the length of the fault distance from the outlet, and the system oscillation. At the same time, through the simulation data of table 3, it is found that an anti-directional impedance element of DP2 may act when a three-phase symmetrical short circuit occurs at the outlet of the line, resulting in $G_m = 1$. However, the anti-directional impedance element of DP3 is correct. Therefore, these three impedance elements can be configured at the same time in each local control unit of bus protection to form redundant configuration to deal with different fault scenarios.

5. Conclusion
In this paper, a distributed busbar protection principle based on the comparison of directional impedance components is proposed. This principle uses three kinds of anti-directional impedance components to determine the fault direction, and comprehensively compares the fault directions of each line to identify the internal and external fault of the busbar. Theoretical analysis and PSCAD simulation results show that the principle can effectively identify the internal and external fault of the busbar, and the protection action is fast, which is less affected by the system oscillation. There is no need for sampling synchronization between different intervals, and it is less affected by data transmission delay. Using state information as an algorithm criterion can effectively solve the problem of hardware synchronization in data acquisition of different interval protection units in existing distributed busbar protection, so that each line can be logically judged independently and the reliability of distributed busbar protection is improved.

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