Research on Line Selection and Positioning of Zero-sequence Current Differential Protection in Distribution Network under the Power Internet of Things in Flexible Grounding System

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Abstract. In 2019, China's power industry proposed the goal of building a “ubiquitous power Internet of Things”. Through the ubiquitous construction of the Internet of Things, the traditional relay protection technology system gradually developed towards the intelligent direction. This paper mainly studies the fast zero-sequence current differential protection using the improved mutation quantity algorithm under the communication mode of power wireless private network. Through MATLAB simulation, it is proved that zero-sequence current differential protection can effectively realize fault location when there are overhead and cable lines in flexible grounding system in complex distribution network.

1. Introduction

In the distribution network system, the neutral point is usually ungrounded, grounded by high resistance or grounded by arc suppression coil. When a single-phase ground fault occurs, the fault current loops through the capacitance to the ground, called a small current ground system. According to the regulations, this condition allows for one to two hours of operation with fault. However, in order to prevent instantaneous fault from developing into permanent fault or single-phase ground fault from developing into interphase short circuit, it is required to find the fault point as soon as possible. There are four common fault location methods for small current grounding systems: 1, Traveling wave method and impedance method; 2, Artificial injection signal method; 3, Matrix algorithm and genetic algorithm; 4, Based on transient zero-order correlation coefficient method [1].
In order to reduce line losses, reduce construction cost, many parts of the distribution network to cancel or higher voltage level distribution network parts, Zhejiang area part of the original 10 kV distribution network upgrade to 20 kV system, in order to make full use of the original 10 kV stock of equipment and facilities, saves the step-up transformation cost, part of the equipment and facilities, such as overhead line and part of the cable line directly boost, but when the single-phase grounding fault occurs, the fault relative to the voltage rises for $\sqrt{3}$ times of phase voltage, boost pressure level of the original 10 kV equipment may reach booster after insulation requirements, prone to breakdown burning equipment[2]. If the traditional small resistance grounding method is adopted, the frequent tripping of transient single-phase grounding fault lines cannot be solved, resulting in the decrease of power supply reliability.

In order to resolve the above contradiction, Zhejiang Jiaxing Tongxiang Electric Power Co., Ltd. adopts a neutral point flexible grounding system. During normal operation, the 20kV neutral point is grounded via the arc suppression coil. After a single-phase ground fault occurs, there is still a parallel grounding small resistance after the delay. The fault current increases rapidly, and the zero-sequence current also increases. The current three-stage protection and zero-sequence protection have simple structure and low operation and maintenance cost. However, due to the long distribution line and many branches, the overhead line and the cable are mixed. It is difficult to meet the selective requirements, which often causes the fault range to expand. Although it can be corrected by reclosing, it cannot meet the user's electricity demand. Although the zero-sequence differential protection has excellent performance, many distribution networks are limited by cost and communication technology. Etc., the exchange of information on both sides of the line cannot be achieved. In 2019, State Grid Corporation of China officially proposed the "General Utilities Internet of Things Network Construction Outline". By improving the communication system construction, connecting equipment and the Internet of Things, it provides a software and hardware foundation for intelligent grid, reduction of staff and efficiency, and the collection of a large number of equipment layer information is effective. Promoted the development of relay protection technology [3].

Through the ubiquitous construction of the Internet of Things, the communication system is continuously strengthened, and the power grid operation is fully monitored to promote the development of the relay protection technology system to the intelligent direction. This paper mainly studies the use of the improved mutation algorithm to achieve fast zero based on the communication mode of the power wireless private network. Sequence current differential protection, and then through MATLAB simulation analysis of zero-sequence current differential protection can effectively achieve the fault location under the overhead line and cable line in the flexible grounding system, avoiding the expansion of the fault range caused by the over-level trip, and improving the relay protection of the distribution network. Level to meet the requirements of system power supply reliability.
2. Neutral point flexible grounding zero sequence network principle

Figure 1. Flexible grounding system wiring schematic
As shown in Figure 1, when the grid is operating normally, the control system monitors the capacitance current of the distribution network in real time, and adjusts the arc suppression coil to the corresponding gear position. The neutral point does not connect to the small resistance (take 20Ω), when single phase grounding occurs. When the fault occurs, the fault current is compensated by the arc suppression coil to prevent the equipment from being burned. The instantaneous fault will disappear quickly. After a certain delay, the permanent fault closes the small resistor series switch to avoid the non-fault relative ground voltage rise and quickly find the fault line. In actual operation, the switch that cuts the small resistance is configured in a double configuration. When there is a ground fault, it cannot be rejected, and it cannot be mistaken during normal operation.

According to the statistics of Tongxiang Power Company's historical data, most of the ground faults are transient faults, which can disappear within 3 seconds. Therefore, set the delay to 3 seconds and put in a small resistor to open the faulty line switch. The line can be automatically reclosed once, then according to Grounding zero sequence overcurrent action delay is 3 seconds to set the small resistance input hold time to 5 seconds, to ensure zero-sequence current protection and reliable action to remove the ground fault. After the fault is removed, exit the small resistance system to resume the grounding operation of the arc suppression coil.

2.1. Neutral point grounded by arc suppression coil [4]

Figure 2. Neutral point arc-suppression coil grounding zero sequence network diagram
When a single-phase ground fault occurs in a neutral point ungrounded system, the fault point is equivalent to a zero-sequence power supply that is opposite in magnitude to the pre-fault condition. An arc is easily generated at the fault point, and the non-fault phase voltage is further increased. Single-phase grounding Developed as a phase-to-phase short circuit fault, resulting in equipment
damage. In order to reduce the fault current, the inductor is compensated for the capacitive current at the neutral point as shown in the figure, because the high-voltage side of the distribution transformer at the end of the 10kV and 20kV feeder lines is usually Y-type wiring, and the zero-sequence impedance infinity is equivalent to disconnection. There are three types of compensation, over-compensation, under-compensation and full-compensation. In order to avoid equipment damage caused by resonant over-voltage, the system usually adopts over-compensation.

The theoretical formula for overcompensation is:

\[ K_p = \frac{I_L - I_{C\Sigma}}{I_{C\Sigma}} \times 100\% \]  (1)

In the formula: \( I_L \) is Compensated inductor current, \( K_p \) is Overcompensation, \( I_{C\Sigma} \) is the sum of the whole system to ground capacitance current.

After compensation, because the system overcompensation degree is 5%~10%, the capacitance current value is relatively small under steady state conditions, and the zero sequence current of the fault line and the non-fault line is the sum of its own capacitance to ground, the zero sequence power direction. They all flow from the busbar to the line. It is impossible to use the zero-sequence current to cut the faulty line like the neutral point direct grounding system. It is impossible to use the zero-sequence current amplitude and reactive power direction of each outgoing line to perform fault line selection and positioning. It is difficult to use. To identify the faulty line.

2.2. Neutral point grounded via small resistor [5]

As shown in Figure 3, when the small resistor series switch is closed, the system becomes grounded via a small resistor as shown in Figure 3, which can effectively prevent the non-fault phase voltage from rising when the single-phase ground fault occurs, because the transformer neutral point is grounded via a small resistor. The equivalent zero-sequence impedance is small, so the fault current is large, and the faulty line can be quickly detected and removed to prevent accidents from expanding. In addition, the principle of overcurrent and zero-sequence protection is simple, the equipment defect rate is low, and the operation and maintenance is simple, but due to There are too many short lines in the feeder line, and overcurrent and zero-sequence protection are difficult to achieve selectivity through time limit. The setting time of the substation outlet is very short. After the trip, the entire line is powered off, causing the fault range to expand. If zero-sequence difference is used. Dynamic protection can effectively improve reliability and reduce power outage time. When a fault occurs, the sum of the currents on both sides is:

\[ I_J = 3I_{OM} + 3I_{ON} = I_{AM} + I_{BM} + I_{AN} + I_{BN} + I_{BN} = I_K + I_C \]  (2)
In the formula, $I_1$ is Flow through the relay, $3I_{0M}$ Near the bus side zero sequence current, $3I_{0N}$ Contralateral zero sequence current, $I_{AM}$ Near the bus side A phase current, $I_{AN}$ Contralateral A phase current, $I_K$ Short circuit current, $I_C$ Capacitor current to ground.

Formula (2) shows that the current flowing through the relay of the zero-sequence differential protection is actually the sum of the fault current and the capacitance current of the line itself to the ground. In the grounding system of the arc-suppression coil, the current at the fault point is small due to compensation. Dynamic protection is difficult to operate correctly.

Differential protection setting formula:

$$I_{set} = K_{er} \cdot K_{st} \cdot K_{np} \cdot I_{0kmax}$$  \hspace{1cm} (3)

$$I_{set} = K_{kel} \cdot I_C$$  \hspace{1cm} (4)

In the formula: $K_{er}$ is The error coefficient is 0.1, $K_{st}$ is the same coefficient is taken as 0.5, $K_{np}$ is the non-periodic component coefficient is 1.5~2, $I_{0kmax}$ is ground fault maximum zero sequence current at the end of this line, $K_{kel}$ is reliability factor.

The zero sequence differential protection setting needs to avoid the unbalance current caused by the maximum through current when the external fault is avoided. At the same time, it should avoid the capacitance current to the ground. If the line is the overhead line, the capacitance current to the ground is small, and if it is the cable capacitance current. Larger values reduce protection sensitivity.

3. Zero sequence voltage starting zero sequence current differential protection principle in flexible grounding system

The flexible grounding system is adopted. When the system detects that a single-phase ground fault has occurred, the small resistor is input after the delay. Since the fault current is the capacitance current to the ground when the small resistance is not connected, the amplitude is not large, and the system has generated zero-sequence voltage. As the starting criterion of the differential, the zero sequence voltage can greatly improve the quick action and sensitivity of the differential protection.

Generally, the distribution network is operated by radiant or ring-opening. In theory, the fault phase current of the fault line is zero in the single-supply operation mode, but the high-voltage side of the distribution transformer at the end of the 10kV and 20kV feeder lines is usually Y-type. When the single-phase grounding occurs in the system, the three-line voltage on the high-voltage side are still approximately symmetrical. At this time, the load current still exists, and the power direction is the power flow direction load, and there is no change before and after the fault. The phase current direction and the amplitude difference are also affected by the load current. Therefore, the zero-sequence current amplitude is used to compare the differential protection. When the FTU is outside the fault, the amplitude of the two sides is approximately equal, and the direction is opposite; The zero-sequence fault current is on the other side and the current is approximately zero.
3.1 Improved mutation method

The FTU of the distribution network detects the current of each phase in real time through the wireless private network. Generally, the load is considered to be three-phase symmetrical and slowly changing. In order to realize fast action, the differential protection uses the zero-sequence current sudden change as the starting criterion, and the sampling is adopted. The period variable is subtracted from the previous sampling period variable, and the variation of three consecutive sampling values satisfies the following conditions as the criterion for starting the fault location:

\[
|i_d(k) - i_d(k-N)| - |i_d(k-N) - i_d(k-2N)| \geq K_e I_\phi \quad (5)
\]

\[
|\frac{i_d(k) - i_d(k-N)}{i_d(k-N) - i_d(k-2N)}| \geq K_d |\frac{i_d(k-N) - i_d(k-2N)}{i_d(k-2N)}| \quad (6)
\]

In the formula: The number of sampling points in one power frequency cycle is \(N\), \(i_d(k)\) is zero-sequence current instantaneous value for the \(k\)th sampling point; \(i_d(k-N)\) is the instantaneous value of the \(k\)th sampling point before a power frequency cycle; \(I_\phi\) is the effective value of the phase current for the system without fault; \(K_e\) is reliability factor, for purpose of avoiding malfunction caused by external disturbance when the load changes are small, take \(K_e = 0.2 - 0.4\); \(K_d\) is for the coefficient of reliability of the sudden change, for purpose of avoiding the malfunction caused by the disturbance when the load change is significant[6-7].

The improved mutation algorithm is used to reduce the effects of load three-phase asymmetry, oscillation, load change and invalid data on the interference mutation algorithm, avoiding protection misoperation and ensuring the reliability of the protection device. The disadvantage is that data of two sampling periods is required. The delay is at least 40s, and the calculation is relatively complicated.

4. MATLAB simulation

![Diagram of neutral grounding system with arc suppression coil](image1)

**Figure 4.** Diagram of neutral grounding system with arc suppression coil

The small current grounding simulation system of 20 kV neutral point arc-suppression coil parallel 20Ω small resistance grounding over-compensation operation mode is established by MATLAB. The system diagram is shown in Figure 1. The parameter setting [8] three-phase voltage source is 110k V;
The rated capacity of transformer T1 is 20 MV, short-circuit loss is 135 kW, no-load loss is 22 kW, and the ratio is 110 kV/20.5 kV. The arc-suppression coil is set according to over-compensation 8%. According to formula (6), the arc-extinguishing inductance can be obtained. 0.265 H, the end of line 1, 2, 3, 43 is connected to transformer T2, the ratio is 20 kV/400 V, the capacity is 640 kVA, the high-voltage side is Y-shaped connection, the low-voltage side Y-shaped connection neutral point is directly grounded, the load is 500 kW, the power factor is 0.85. From top to bottom are line1, line2, line3, line41, line, line42, branch 41, line43, branch42, line44.

| Table 1. Line impedance parameter table |
|----------------------------------------|
| line type | resistance/Ω · km⁻¹ | inductance/mH · km⁻¹ | capacitance/µF · km⁻¹ |
| Positive sequence | 0.170 | 0.320 | 1.017 | 3.560 | 0.115 | 0.006 |
| Zero sequence | 0.270 | 2.700 | 0.255 | 1.109 | 0.376 | 0.276 |

| Table 2. Line length and classification |
|-----------------------------------------|
| line name | Line 1 | Line 2 | Line 3 | Line41 | Line42 | Branch road 41 | Line43 | Branch road42 |
| line type | Overhead lines | Overhead lines | Overhead lines | Overhead lines | Overhead lines | Overhead lines | Overhead lines | Overhead lines |
| length (km) | 10 | 13 | 8 | 10 | 10 | 15 | 15 | 15 |

According to the historical data, most of the instantaneous grounding of Tongxiang Power Supply Co., Ltd. can be extinguished within 3 seconds. Therefore, the delay is 3 seconds to close the parallel small resistance switch. In this paper, the waveform can be displayed more easily for simulation, so the single-phase grounding is set at 0.3 seconds. The delay is 0.3 seconds to input the parallel small resistance. The side of the line close to the busbar is called the busbar side, and the end of the line away from the busbar is called the opposite side. The line 1 is close to the busbar side d1, and the line 41 is close to the busbar side d2. And the opposite side d3, the line 42 is close to the bus side d4, the transition resistance is simulated at 0Ω, 150 Ω, 300 Ω, respectively. The line 1 is connected in series with three resistors respectively, 1, 5, 10Ω. The normal operation of the system has three-phase unbalanced zero-sequence current.

**Figure 5.**
Zero sequence voltage measurement at fault d2

**Figure 6.**
Bus-side zero-sequence current measurement at fault d2
It can be clearly seen from Fig. 5 and Fig. 6 that the system generates a large zero-sequence voltage at 0.3 seconds. When 0.6 seconds is input into the parallel small resistor, the zero-sequence voltage of the fault line continues to maintain a relatively large value without change, and the faulty line power supply The side zero-sequence current and current are obviously increased, because the normal operation of the line is asymmetrical, there is a zero-sequence current of 0.2A, the asymmetry in the actual running distribution network is large, and the neutral point offset is serious, there will be a large zero-sequence current.

Fig.7 shows that after the single-phase grounding, the fault phase current is slightly decreased when the busbar side is measured. When the small resistor is grounded, the fault current increases rapidly, and the phase is always the same as the non-faulty line current and the busbar side current is opposite because The high voltage side of the transformer connected to the end of line 1 is Y wiring mode, so the three-phase line voltage remains symmetric. After the fault, the single-phase current that is not close to the power supply side is affected by the load, regardless of whether single-phase grounding occurs, and the zero-sequence current is due to the load. The high voltage side of the side transformer is a Y-shaped wiring, and the zero-sequence current is zero. Since the opposite side current is zero, the power direction differential protection cannot be used for discrimination.

| d_1 | Line 1 Zero sequence current value (A) | Line 2 Zero sequence current value(A) | Line 41 Zero sequence current value (A) | Line 42 Zero sequence current value (A) |
|-----|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
|     | busbar side | Opposite side | busbar side | Opposite side | busbar side | Opposite side | busbar side | Opposite side |
| 0   | -532        | 0             | 35.3        | 0             | 50.2        | -49           | 48           | -1           |
| 150Ω| -53         | 0             | 35.3        | 0             | 50.2        | -49           | 48           | -1           |
| 300Ω| -35         | 0             | 35.3        | 0             | 50.2        | -49           | 48           | -1           |
|     | 0Ω          | 1.1           | 0           | 35.3          | 0           | -532          | 20.8         | 48           | -1           |
|     | 150Ω        | 1.1           | 0           | 35.3          | 0           | -53           | 20.8         | 48           | -1           |
|     | 300Ω        | 1.1           | 0           | 35.3          | 0           | -35           | 20.8         | 48           | -1           |
|     | 0Ω          | 1.1           | 0           | 35.3          | 0           | -479          | 49.5         | 48           | -1           |
|     | 150Ω        | 1.1           | 0           | 35.3          | 0           | -94           | 49.5         | 48           | -1           |
|     | 300Ω        | 1.1           | 0           | 35.3          | 0           | -64           | 49.5         | 48           | -1           |
|     | 0Ω          | 1.1           | 0           | 35.3          | 0           | -469          | 468          | -466.5       | -1           |
|     | 150Ω        | 1.1           | 0           | 35.3          | 0           | -90           | 87.5         | -85.9        | -1           |
|     | 300Ω        | 1.1           | 0           | 35.3          | 0           | -59           | 57.9         | -56.1        | -1           |

It is stipulated that the bus line flow direction is positive direction. Because the current phase
comparison principle cannot be adopted, the current amplitude comparison method is used to realize the differential protection. The three-phase unbalance will have the initial zero sequence current. It can be obtained from Table 3. The transition resistance is actually equivalent. In parallel with the equivalent load, the larger the transition resistance, the smaller the fault current and zero-sequence current, and the zero-sequence current of the transformer near the load side is always zero. There is a formula available. The sum of the zero-sequence current flowing through the relay is actually the fault current and The line is non-fault relative to the capacitive current. If the neutral point is grounded by the arc suppression coil, it is close to full compensation, the fault current is small, and the zero sequence differential protection cannot work normally. Since the line 42 is a cable line, the capacitor current is distributed to the ground. Larger, the sum of the currents on both sides of the line 42 is also very large, so the shorter the line, the smaller the distributed capacitor current, the greater the load current, the better the sensitivity of the zero-sequence current differential protection is better than the fault phase current differential protection. It is not affected by the three-phase symmetrical load during normal operation.

In summary, table 3 shows that the current amplitude initiated by the zero-sequence voltage and the sudden-change algorithm is relatively differential protection, and the fault point can be effectively positioned under normal conditions.

5. Conclusion

In the small-current grounding system grounded by arc suppression coil, when single-phase grounding fault occurs, the fault current, zero-sequence current and negative sequence current are small, due to the three-phase asymmetry or load variation of the system itself, and the numerous branches and overhead cables of the distribution network hybrid phenomena are common, the load changes rapidly, the line transaction rate is high, and the distributed power supply has increased in recent years. The reliability of fault line selection and positioning of small current grounding systems has always been an intractable problem [9].

Based on the flexible grounding system of Jiaxing Tongxiang Electric Power Co., Ltd., through the construction of a stable and reliable communication system in the Internet of Things, zero-sequence current differential protection is realized, which has the following advantages:

1. It is not affected by the system load. Because the neutral point of the transformer at the end of the feeder is not grounded, the load current still exists after the single-phase ground fault occurs.

2. Due to the influence of three-phase unbalance, the mutation algorithm can avoid the influence of zero-sequence current during normal operation, and is not susceptible to shock and slow change.

3. It is easy to be affected by the distributed capacitance current of the line, especially the long-distance cable line, but the cable line is less likely to have a single-phase grounding fault.

4. It is less affected by the transition resistance. After the neutral point is grounded by a small resistor, the excessive resistance is rapidly reduced, and the zero-sequence differential protection is sensitive.

5. It can reduce the small resistance input retention time, quickly remove the fault current, to prevent burning equipment.

Through MATLAB simulation analysis, zero-sequence current differential protection can effectively realize the fault analysis under the overhead line and cable line in the flexible grounding system, avoiding the expansion of the fault range caused by the over-level trip, improving the relay
protection level of the distribution network, and satisfying the reliable power supply of the system requirements.

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