Application of Distribution Network Current Differential Protection Based on Ubiquitous Internet of Things in Line Selection and Location of Small Current Grounding System

Weibing Yin¹, Chaoli Feng¹, Jianli Shi², Jianqin Lu² and Lei Wang³*  
¹State Grid Jiaxing Electric Power Supply Company  
²State Grid Haiyan Electric Power Supply Company  
³Shanghai University of Electric Power  
*Corresponding author’s e-mail: 2005000098@shiep.edu.cn

ABSTRACT: In order to find the fault point of one-phase grounding in distribution network as soon as possible and prevent instantaneous fault from developing into permanent fault or inter-phase short circuit, Tongxiang Electric Power Company of Jiaxing, Zhejiang Province adopts neutral point flexible grounding system, which solves the difficulty of fault location and avoids the malpractice of frequent tripping of the system. Based on the communication mode of power wireless private network, the feasibility of implementing fast differential protection in distribution network by using improved mutation algorithm is analyzed through MATLAB simulation. Under the influence of overhead line, cable line, the first or the end of line and transition resistance in flexible grounding system, differential protection can effectively reduce the extension of fault range, improve the relay protection level of distribution electric network to meet the reliability requirements of power supply system.

1. Introduction

In distribution network of power system, neutral point is usually grounded by non-grounding, high resistance grounding or arc suppression coil grounding. When single-phase grounding occurs, the system is allowed to operate with a fault for one to two hours because the three-phase line voltage is still symmetrical and the fault current is small. In practical application, it is often required to find the fault point as soon as possible to prevent transient fault from developing into permanent fault or single-phase grounding from developing into phase short circuit. Because the fault current is very small and the distribution line parameters, especially the overhead line parameters, are greatly affected by the environment, the current changes with the line impedance parameters, it is difficult to distinguish the fault line and non-fault line in the case of grounding the arc suppression coil.

Tongxiang Electric Power Company in Jiaxing of Zhejiang province adopts flexible grounding system with neutral point, which is grounded by arc suppression coil at 20 kV neutral point in normal operation. When one-phase grounding fault occurs, the system measures a higher zero-sequence voltage and then puts into parallel grounding small resistance. The fault phase current increases rapidly. There are many feeders, branches and rings in the actual distribution electric network. It is difficult for traditional three-stage current protection to meet the requirements of selectivity and sensitivity because of the change of parameters caused by environmental impact and the wide range of operation modes. Although differential protection has excellent performance, many distribution
electric networks are unable to realize information exchange on both sides of the line due to cost and communication technology constraints, so it is difficult to put it into practical application.

In 2019, State Grid Corporation of China formally proposed the strategic goal of "building a full-service ubiquitous power Internet of things". The construction of ubiquitous power Internet of things will greatly enhance the ability of collected information of distribution electric network operation status, thus ensuring the access of distributed energy, improving the elastic bearing capacity of new loads, and meeting the diverse energy needs of users. Ubiquitous Internet of Things (Ubiquitous Internet of Things) will make great changes to traditional distribution network protection technology through comprehensive data acquisition, reliable communication and high-performance information processing[1].

In this paper, the feasibility of fast differential protection based on improved mutation algorithm is studied under the ubiquitous Internet of Things. The MATLAB Simulation analysis shows that differential protection can effectively realize overhead lines, cable lines, the first or the end of lines and transition resistance in flexible grounding system. Under the influence of fault location, avoid overstepping trips to cause the expansion of fault scope, reduce the reliability of power supply system, improve the level of relay protection of distribution network, meet the requirements of power supply reliability of the system.

2. Working Principle of Flexible Grounding System
Jiaxing Tongxiang Power Supply Company used the original 10 kV equipment to avoid the non-fault phase voltage rising too much when one-phase fault happened in order to save cost in the 20kV transformation. In the initial stage, the small resistance grounding method was adopted[2]. However, 179 trips occurred in the 20kV line in 2011, among which 141 trips were caused by one-phase grounding fault. It accounted for 78.8% of the total tripping times. In order to reduce the tripping rate of one-phase grounding fault, the neutral point of 20kV (triangular connection) side is transformed into arc suppression coil by grounding. When the one-phase grounding fault occurs, the system is connected to the small resistance in parallel. When the instantaneous fault occurs, the system will not remove the fault, which greatly reduces the tripping rate. When the permanent fault occurs, the small resistance can be connected in parallel. It is difficult to select and locate one-phase grounding faults by removing faulty lines, but grounding by arc suppression coil.

The principle of flexible grounding mode is shown in Fig. 1. When the power grid is in normal operation, the arc suppression coil is connected to the power grid through the neutral point. The control system calculates the capacitance current of the power grid in real time, adjusts the arc suppression coil to the corresponding gear, and the neutral point is grounded through the arc suppression coil. When one-phase grounding fault occurs in distribution network, arc suppression coil can effectively compensate the capacitive current of power network, reduce the fault current, avoid frequent tripping of fault line and arc burning equipment at fault point. If the fault disappears, the system can work normally; if the fault is permanent grounding fault, the parallel small resistance circuit can be closed by the control system after a certain delay. In the neutral series switch, the neutral point is grounded by small resistance, and the fault is removed by three-stage current protection.
The neutral point of 20kV side of distribution network in TongXiang area has been upgraded to parallel grounding by arc suppression coil through small resistance grounding system step by step, which not only solves the problem of insufficient voltage withstanding level of the original equipment in boost transformation, but also avoids frequent trips caused by most instantaneous one-phase grounding faults[2][3]. After the transformation of 20kV system in Tongxiang area, the input rate of small resistance is 14.12%. The trip rate of the transmission line has been reduced from 80% to 4.75%, which effectively solves the problem of frequent trips and improves the reliability of power supply.

When a permanent one-phase grounding fault occurs, the fault point is often accompanied by the transition resistance, such as the conductor drops on the grass. Because the transition resistance will reduce the fault current, when the transition resistance is too large, the fault current is too small to identify, and the three-stage current protection can not meet the selectivity requirements. Therefore, Jiaxing Tongxiang Electric Power Company plans to use wireless technology through the construction of ubiquitous Internet of Things. Private network transmits electric quantity information to realize current differential protection of distribution network, reduces power outage time and improves power supply reliability of distribution network.

2.1 Characteristic of Electrical Quantity of Ungrounded Neutral System with One-Phase Grounding [4]

When a one-phase grounding fault occurs in a neutral-point ungrounded system, the whole system will generate a zero-sequence voltage opposite to the fault phase voltage in the same direction. The non-fault relative ground voltage rises to 3 times of the phase voltage. The circuit is composed of grounding impedance (reactance). Because the capacitance value of the line to the ground is small, the fault phase current is small, and it is difficult to distinguish it from the normal load current.

C-Phase One-Phase Grounding at the Head of Line \( \hat{U}_{CD} = 0 \)

\[
\hat{U}_{AD} = \sqrt{3} \hat{E}_C e^{-j150^\circ}
\]

\[
\hat{U}_{BD} = \sqrt{3} \hat{E}_C e^{j150^\circ}
\]

In the formula: \( \hat{U}_{CD}, \hat{U}_{BD}, \hat{U}_{AD} \) are three-phase ground voltage after fault, \( \hat{E}_C \) is C phase potential before fault.

Zero-sequence current of feeder is usually used as the criterion to distinguish fault line from non-fault line.

\[
3I_{o1} = 3U_\varphi \omega (C_0 \Sigma - C_{01})
\]

\[
3I_{o2} = 3U_\varphi \omega C_{02}
\]

\[
I_k = 3U_\varphi \omega C_0 \Sigma
\]
In the formula: \(3I_{01}, 3I_{02}\) are zero-sequence currents of line 1 and 2. \(I_k\) is short-circuit current. \(U_0\) The phase voltage before \(U_0\) phi fault. \(C_0\) The sum of ground capacitance of \(C_0\) fault components in the whole system. \(C_{01}\) and \(C_{02}\) are the non-fault relative ground capacitors of line 1 and 2.

When one-phase grounding fault occurs in neutral ungrounded system, the zero-sequence current of outgoing line has the following characteristics:

Zero-sequence current of non-fault line is its own capacitive current to ground, and the actual direction of reactive power flows from bus to line.

The zero-sequence current of fault line is the sum of capacitive current of non-fault elements to the ground, and the reactive power flows from the line to the bus.

The fault point current is the sum of capacitive current of non-fault components to the ground.

In practical application, the more feeders in substation, the greater the zero-sequence current of one-phase grounding fault line, the more advantageous it is to distinguish non-fault and fault link by using different magnitude and power direction of zero-sequence current of fault line and non-fault line. However, if there are only two outgoing lines in substation, the magnitude difference of zero-sequence current of two lines will occur. Fault line selection is not very small, it is difficult to achieve fault line selection, only using zero sequence reactive power direction for fault line selection.

2.2 Characteristic of Electrical Quantity in One-Phase Grounding of Neutral Point Grounded by Arc Suppression Coil

Nowadays, cable is widely used to transmit electric energy in urban distribution electric network. When one-phase grounding fault occurs in neutral ungrounded system, if the fault point current is large, arc will be generated at the fault point, which will further increase the voltage of non-fault phase and cause equipment insulation to be damaged.

In order to reduce the fault current, a large inductance is usually installed at the neutral point of the transformer to offset the capacitive current. There are usually three ways: over-compensation, under-compensation and full compensation. The system mostly adopts over-compensation. Generally, the over-compensation is between 5% and 10%. As shown in Figure 1, when the small resistance series switch is turned on, the system is composed of three modes: over-compensation, under-compensation and full-compensation. In the actual operation of the system, the capacitive current to the ground is not a fixed value, so 20% of the capacity of the upper transformer is usually used as the standard for calculating the arc suppression coil[2][3].

The theoretical formula of over-compensation is as follows:

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

(6)

In the formula: \(I_L\) is the compensated inductance current, \(K_p\) is over-compensation. \(I_{C\Sigma}\) is the sum of capacitive currents to the ground of the whole system.

After compensation, theoretically, the zero-sequence current of fault line and non-fault line is the sum of their capacitive currents to the ground and the direction is the same, so the zero-sequence current amplitude and reactive power direction of each outgoing line can not be used for fault line selection and location.

2.3 Characteristics of electrical quantity when the neutral point is grounded single-phase by small resistance [5]

As shown in Fig. 1, when the small resistance series switch is closed, the system becomes grounded by the small resistance (the resistance is 20Ω), which can effectively limit the overvoltage of one-phase grounding fault. Because the current of the fault line is large, theoretically the overcurrent protection has better sensitivity, and the fault line can be detected and removed quickly, thus reducing the fault. In addition, the principle of over-current protection is simple, the defect rate of equipment is low, and the operation and maintenance is simple. However, due to the multiple branches of distribution network outgoing lines and the existence of transition resistance, it is difficult to achieve selectivity
only by using the magnitude of current to distinguish the setting time limit. As a result, the blackout scope is enlarged. If differential protection is adopted, the reliability can be effectively improved and the blackout time of users can be reduced.

Differential protection setting formula:

\[ I_{set} = K_{er} \cdot K_{st} \cdot I_{np} \cdot I_{kmax} \]  

(7)

In the formula: \( K_{er} \) is 0.1 for error coefficient, \( K_{st} \) homotype coefficient is 0.5, \( K_{np} \) the coefficient of \( I_{np} \)aperiodic component is 1.5~2, \( I_{kmax} \) is maximum through short circuit current in external fault

3. Implementing current differential protection for fault line selection and location by using improved mutation algorithm

3.1 Improved Mutation Method [6][7]

FTU detects phase current in real time through wireless private network. It is generally considered that the three-phase load is symmetrical and changes slowly. In order to reduce the disturbance of load fluctuation and inefficient data to mutation algorithm and realize fast fault location, current mutation is used as starting criterion for differential protection. By subtracting the last sampling period variable from the sampling period variable, the variation of three consecutive sampling values satisfies the following conditions as the criterion of fault location start-up:

\[ \left| I_d(k) - I_d(k-N) \right| - \left| I_d(k-N) - I_d(k-2N) \right| \geq K_e I_\phi \]  

(8)

\[ \left| I_d(k) - I_d(k-N) \right| - \left| I_d(k-N) - I_d(k-2N) \right| \geq K_d \left| I_d(k-N) - I_d(k-2N) \right| \]  

(9)

In the formula: \( I_d(k) \) is the instantaneous value of fault phase current at the kth sampling point; \( I_d(k-N) \) is the instantaneous value of the kth sampling point in a cycle wave front, and the sampling point of a power frequency cycle is N; \( I_\phi \) is the effective value of the phase current when the system is fault-free; \( K_e \) is the reliability coefficient. \( K_e=0.2~0.4 \) is chosen to avoid the misoperation caused by disturbance when the load changes little; \( K_d \) is the reliability factor of sudden change, in order to avoid the misoperation caused by disturbance when the load changes significantly.

The improved mutation algorithm can effectively reduce the protection malfunction caused by system oscillation and load fluctuation, and ensure the reliability of the protection device. The disadvantage is that the data of two sampling cycles need to be used, and the calculation is complex, with a delay of at least 40 ms.

3.2 Principle of Zero Sequence Voltage Start-up Current Differential Protection in Flexible Grounding System

In flexible grounding system, when a one-phase grounding fault occurs, the system will generate a large zero-sequence voltage before it is put into small resistance. Using zero-sequence voltage as the starting criterion of differential protection can effectively improve the sensitivity of differential protection and reduce the impact of transition resistance.

Usually the distribution network is operated by radiation mode or open loop mode. In theory, the downstream fault phase current of the fault line is zero under the single power supply mode. If the power direction is compared between the two sides, it is difficult to determine the power direction because of the small voltage and current. Therefore, the current amplitude based on Kirchhoff’s current law is adopted to compare the differential protection. In the case of out-of-zone fault, the amplitude of current measured by FTU on both sides is approximately equal and the direction is opposite; in the case of in-zone fault, the fault current on one side is approximately zero while the current on the other side is approximately zero.

If the distribution electric network operates in closed-loop mode, the outside fault mode is the same as that in open-loop mode; when the inside fault mode, the current amplitude on both sides is larger and the power direction is the same.
3.3 MATLAB Simulation

A simulation system of 20 kV neutral grounding with 20Ω small resistance grounding in parallel via arc suppression coil is established by using MATLAB Simulink. The system diagram is shown in Figure 1. Three-phase voltage source is 110 kV, rated capacity of transformer T1 is 20 MVA, ratio is 110 kV/20.5 kV, arc suppression coil is set up according to over-compensation 8%, arc suppression inductance is 6H according to formula (19), simulation model has four outgoing lines, line 1, 2, 3, 4, line 3 is cable, others are overhead lines, line 4 contains trunk. Lines 41, 42, 43, branch 41, 42, length line 1 is 3 km, line 2 is 5 km, line 3 is 7 km, line 41, 42 is 10 km, line 43 is 15 km, branch 41, 42 is 15 km, line 1, 2, 43 terminal transformer T2, conversion ratio 20 kV/400V, capacity 640 Kva, high voltage side Y-connection, low voltage side Y-connection neutral point direct grounding, connection load 50 km. 0 kw, power factor 0.85[8].

| Line type | resistance /Ω·km⁻¹ | inductance /mH·km⁻¹ | Capacitance /μF·km⁻¹ |
|-----------|---------------------|----------------------|----------------------|
|           | positive sequence   | zero sequence        | positive sequence     | zero sequence         |
| Overhead line | 0.170            | 0.320                | 1.017                | 3.560                 |
|            | 0.115              | 0.006                |                      |                      |
| Cable     | 0.270              | 2.700                | 0.255                | 1.109                 |
|           | 0.376              | 0.276                |                      |                      |

According to the statistics of historical data, most of the instantaneous grounding can be extinguished by arc suppression coil in 3 seconds, so setting a delay of 3 seconds to put into parallel small resistance. In order to display the waveform faster and better in the oscilloscope in simulation, this paper sets a one-phase grounding in 0.3 seconds, and puts into parallel small resistance in 0.3 seconds, and to line. The side near the bus at the end of the road is called the bus side, and the end far from the bus is called the opposite side. Line 1 is close to the bus side d₁, line 41 is close to the bus side d₂ and the opposite side d₃, line 42 is close to the bus side d₄, and the transition resistance is simulated at 0 Ω, 150 Ω and 300 Ω, respectively.

![Fig.2 Zero Sequence Voltage Measurement in d₂ Fault](image1)

![Fig.3 Measurements of Phase Current at Bus Side Fault under d₂ Fault](image2)

It can be clearly seen from figs. 2 and 3 that the system produces a large zero-sequence voltage in
0.3 seconds, but the steady-state magnitude of the fault phase current changes significantly. The offset time axis decays with time due to compensation inductance. When a small shunt resistance is put into operation in 0.6 seconds, the zero-sequence voltage of the fault line keeps a relatively large value unchanged. The fault phase current on the power side of the fault line increases obviously.

As shown in Fig. 4, after one-phase grounding, the measured fault phase current at the bus side decreases slightly. After small resistance grounding, the fault current increases rapidly, while the side current almost keeps unchanged at 22.4A, and the phase is always the same as that of the non-fault line and opposite to that of the bus side current, which is almost the same as that of the bus current before the fault, because of the transformer connected at the end of line 1. The high voltage side of the converter is connected by Y mode, so the three-phase line voltage remains symmetrical. The magnitude of the one-phase current near the power side after the fault is affected by the load, which is independent of whether the one-phase grounding occurs or not.

![Fig. 4 Fault Phase Current Waveform of Line 1 in d_1 Fault](image_url)

Tab.2 Fault phase current of each line during fault

| Fault Phase Current Value of Line 1 (A) | Fault Phase Current Value of Line 2 (A) | Fault Phase Current Value of Line 41 (A) | Fault Phase Current Value of Line 42 (A) |
|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Busbar side                            | Opposite side                          | Busbar side                            | Opposite side                          |
| d_1                                    |                                        |                                        |                                        |
| 0Ω                                     | 533                                    | -22.4                                  | 23                                     |
| 150Ω                                   | 53                                     | -22.4                                  | 22.8                                   |
| 300Ω                                   | 35                                     | -22.4                                  | 23.1                                   |
| d_2                                    |                                        |                                        |                                        |
| 0Ω                                     | 23                                     | -22.4                                  | 23                                     |
| 150Ω                                   | 23                                     | -22.4                                  | 22.8                                   |
| 300Ω                                   | 23                                     | -22.3                                  | 23.1                                   |
| d_3                                    |                                        |                                        |                                        |
| 0Ω                                     | 23                                     | -22.3                                  | 23                                     |
| 150Ω                                   | 23                                     | -22.3                                  | 22.3                                   |
| 300Ω                                   | 23                                     | -22.3                                  | 23.1                                   |
| d_4                                    |                                        |                                        |                                        |
| 0Ω                                     | 23                                     | -22.3                                  | 23                                     |
| 150Ω                                   | 23                                     | -22.3                                  | 22.3                                   |
| 300Ω                                   | 23                                     | -22.3                                  | 23.1                                   |

From Table 2, it can be concluded that the principle of current phase comparison can not be used, but the method of current amplitude comparison can be used to realize differential protection, because the phase of current on both sides is opposite whether there is a fault in the area or not. The magnitude of the fault phase current near the power supply side is related to the transition resistance. The larger the transition resistance, the smaller the fault current and the smaller the sum of the current on both sides of the line. In this simulation, when the transition resistance is more than 1800Ω, the current on both sides of the fault line is almost the same.

In summary, Table 2 shows that differential protection based on zero sequence voltage and mutation algorithm can effectively locate fault points under normal conditions.
3.4 conclusion
When one-phase grounding fault occurs in small current grounding system grounded by arc suppression coil, zero and negative sequence currents are relatively small. Due to the three-phase asymmetry or load variation of the system itself, the distribution network has many branches and overhead cable mixing phenomenon is widespread. The short-term variation of load is large, and the line variation rate is high. In addition, in recent years, the distributed power system has many branches and overhead cables. The reliability of fault line selection and location for small current grounding system is always a difficult problem to solve due to the influence of a large number of factors[9][10].

Based on the flexible grounding system of Tongxiang Electric Power Company in Jiaxing City, through the construction of a stable and reliable communication system which is ubiquitous in the Internet of Things, the traditional relay protection technology system gradually develops towards the direction of intelligent and intelligent decision-making and dispatching. Zero-sequence current differential protection has the following characteristics:

- The influence of system load is great. Because the neutral point of transformer at the end of feeder is not grounded, the load current still exists after single-phase grounding fault.
- The catastrophe algorithm can avoid the influence of phase current in normal operation, and is not easily affected by oscillation and slow change.
- The fault phase voltage is zero and the fault phase line has no distributed capacitive current, which is not affected by the distributed capacitive current of the line.
- It is less affected by the transition resistance. After the neutral point is grounded by small current, the transition resistance decreases rapidly.

Finally, the feasibility of adopting the current differential protection method in distribution network is verified by the simulation of MATLAB. It can realize fast and accurate line selection and location. It not only improves the accuracy of fault location, but also meets the actual engineering needs, and greatly improves the reliability of power supply in distribution network.

Reference
[1] Y.J.Zhang, T.Yang, G.Y.Meng. Review and Prospect of Ubiquitous Power Internet of Things in Smart Distribution System[J]. power construction, 2019,40(06):1-12.
[2] J.Q.Xu. Application of Flexile GroundMethod in 20kV Distribution Network[J]. Science and technology square. 2013(07):102-105.
[3] H.Xue, Y.J.Li, H.Cheng. Criterion for Single-phase Grounding Fault Line Selection for Small Current Grounding System by Using Zero Sequence Power Direction[J]. Guangdong Electric Power, 2018,31(04):132-138.
[4] H.F.Liang, M.N.Jia, L.M.Di. An inpeoved method of small current grounding fault location[J].Journal of Shandong University of Technology (Natural Science Edition), 2017,31(03):36-41
[5] Q.Liu, D.S.Zhao, L.S.Xiao, X.D.OuYang. Optimization Measures for Neutral Point Grounding Mode of Small Current Grounding System of Guangdong Power Grid[J]. Guangdong Electric Power,2017,30(12):124-129.
[6] B.H.Zhang. System Protective Relaying[M]. BeiJing. China Electric Power Press.
[7] Q.L.Pang, Y.C.Liu, X.N.Li, J.Sun, S.L.Wang. Current polarity comparison based fault location for active distribution network[J]. Power system protection and control, 2018,46(20):101-108.
[8] https://doi.org/10.19635/j.cnki.csu-epsa.000181.
[9] M.H.Liu, T.Fang, Y.Jiang, X.J.Zeng, Y.H.Huang, G.Wei. Fault Line Selection Method Based on Correlation Analysis of High-frequency Components[J]. Journal of Electric Power Systems and Automation, 2017,29(02):101-106+128.
[10] K.W.Xiao, X.P.Xu, Z.G.Zhao, Q.S.Tian, S.B.Liang, C.Li. Active Single Based on Power Disturbance Signal Experimental Study on Fault Location Technology of Phase[J]. Electronic technology, 2018,31(06):36-38+47.