Research on neutral point grounding mode and single-phase earth fault location of medium voltage island microgrid

Shi Kejian1*, Tian Ye1, Wu Jing1, Li Guanhua1, Qi Haixing2, Geng Zhenxin3, Xu Jianyuan3

1State Grid LiaNing Electric Power Research Institute, Liaoning, Shenyang 110000, China.
2Beijing DHHB Power Science and Technology Co., Ltd, Haidian District, Beijing 100085, China.
3School of Electric Engineering, Shenyang University of Technology, Liaoning, Shenyang 110870, China.
*Corresponding author’s e-mail: kejian1986@163.com

Abstract. For medium voltage islanding microgrid, the voltage clamp of the main network neutral arc suppression coil or small resistance is lost. Multiple PTs parallel operation will occur because different entities of a microgrid independently measure the voltage. It is necessary to consider the influence of multi PTs ferroresonance on the neutral grounding mode of islanding microgrid. The neutral point ungrounded, neutral point grounded by arc suppression coil and neutral point grounded by small resistance are analyzed respectively, considering multi PTs ferroresonance and single-phase earth fault location, it is determined that the islanded microgrid adopts neutral point grounded by small resistance. On this basis, the zero sequence current distribution is used to locate the single-phase earth fault. Finally, a simulation example is built to verify the correctness of the proposed method.

1. Introduction
A Microgrid is a small power generation and distribution system composed of distributed power supply, power load, distribution settings, energy storage devices, monitoring, protection devices, and it is one of the future development directions of power grid. It is very common for a microgrid to connect to a 10–35kV Power Grid, so it is very important to determine the neutral point grounding mode and single-phase earth fault location technology of the island microgrid. In general, a microgrid is composed of several operating entities. Each of them needs to measure voltage independently through an electromagnetic voltage transformer(PT). Therefore, compared with the traditional high-voltage distribution network, there are many parallel operations of multiple PTs in the microgrid. The operation modes of a microgrid include grid-connected mode and island mode[1-3]. In the island mode, the microgrid will lose the voltage clamp of the main network neutral arc suppression coil or small resistance. At this time, the PTs in parallel operation are more likely to have ferroresonance, which will affect the selection of system neutral grounding mode and fault location.

Many experts and scholars have studied the neutral grounding mode of low voltage microgrids[4-5], but the influence of ferroresonance on the neutral grounding mode of an islanding microgrid is not considered. Many experts have done a lot of research on the mechanism and suppression measures of ferroresonance. In reference [6-8], the mechanism and mathematical model of ferroresonance are...
described. In reference [9-11], measures for eliminating ferroresonance are described and different methods for eliminating ferroresonance are compared. In reference [12-14], the detection and identification technology of ferroresonance is analyzed and studied. However, the above literature only discusses the mechanism and suppression method of ferroresonance in single PT system, but few studies on the mechanism and suppression measures of multi PTs ferroresonance in island microgrid.

In this paper, three operation modes of medium voltage islanding microgrid are analyzed: ungrounded neutral point, grounded through arc suppression coil and grounded through small resistance, considering the multi PTs ferroresonance and single-phase earth fault location of island microgrid, it is determined that the neutral point of the system is grounded through small resistance. On this basis, the zero sequence current distribution feature of the system is used to locate the single-phase earth fault. Simulation analysis verifies the correctness of this method.

2. Study on neutral point grounding mode
In islanding mode, it is very easy to have multiple PTs parallel operation in a microgrid. As shown in Figure 1, when the main network fails or the power quality does not meet the requirements, the point of common coupling (PCC) is disconnected. At this time, the microgrid and the main network are separated and enter the island mode, and the neutral point of the main network grounded by small resistance or arc suppression coil is lost.

2.1. Ungrounded neutral system
For the ungrounded neutral system, the voltage clamp of the neutral point of the main network is lost and multiple PTs parallel, so ferroresonance is easy to occur.

As the inverter of the inverter type distributed power is equipped with saturation link to prevent over-current of the inverter, for ungrounded neutral system, the short-circuit current of the system is small when single-phase ground fault occurs, which is not conducive to fault location.

2.1.1. Analysis of single phase ferroresonance circuit.
In order to facilitate the analysis of multi PTs ferroresonance, the single phase ferroresonance circuit is analyzed first, and the resistance in the system is not considered. Single phase ferroresonance circuit is shown in Figure 2; \( E \) is the effective value of the power voltage; \( L \) is the excitation inductance of the PT; \( C \) is the system capacitance, which is a fixed value; \( \psi \) is the inductive flux linkage.

![Figure 1. Structure diagram of microgrid](image1)

![Figure 2. Single phase ferroresonance circuit](image2)
The mechanism of ferroresonance in multi PTs parallel system is analyzed by graphic method. The volt ampere characteristics of single-phase ferroresonance circuit are shown in Figure 3.

![Figure 3. Characteristic curves of ferroresonance in the cases of multi-PT parallel and single PT](image)

Set $\Delta U(I)$ as the absolute value of circuit voltage drop sum. $I_1$ is $U_c(I)$ which is the volt ampere characteristic of capacitance; $I_2$ is which is volt ampere characteristics of single PT inductance $L$ ; $I_3$ is $U_L(I)$ which is volt ampere characteristics of the equivalent inductance $L'$ of multi PTs parallel connection; $I_4$ is $\Delta U(I)=|U_c(I)-U_c(I)|$; $I_5$ is $\Delta U(I)=|U_L(I)-U_c(I)|$. $a_1$ is the stable resonance point of multi PTs parallel operation, $a_2$ is stable resonance point of single PT.

It can be seen from the Figure 3 that the stable non resonant points $b_1$ and $b_2$ are similar in both cases. The excitation from $b_1$ to $a_1$ is smaller than that from $b_2$ to $a_2$. Therefore, the ferroresonance of multi PTs parallel is easier than the ferroresonance of single PT.

2.1.2. Analysis of three phase ferroresonance circuit.
Three phase ferromagnetic resonance circuit is shown in Figure 4:

![Figure 4. Three phase ferroresonance circuit](image)

$e_A e_B e_C$ is the three phase power voltage, $L_A L_n L_C$ is excitation inductance of three phase PT, $R_A R_n R_C$ is high voltage side resistance of PT, $C$ is capacitance to ground. For the convenience of analysis, it is assumed that the inductance flux linkage of parallel PT in-phase winding is equal and both are $\Psi_i$ ($i=A, B, C$). $u_0$ is the neutral point voltage. According to Kirchhoff Law, the equations can be listed and arranged as follows:

$$\begin{align}
\frac{d\psi_A}{dt} &= -R_A i_A + u_0 + e_A \\
\frac{d\psi_B}{dt} &= -R_B i_B + u_0 + e_B \\
\frac{d\psi_C}{dt} &= -R_C i_C + u_0 + e_C \\
\frac{du_0}{dt} &= -\frac{m_i}{3C} - \frac{m_i}{3C} - \frac{m_i}{3C}
\end{align}$$

(1)
The neutral point voltage $u_0$, phase voltage and phase current can be calculated by solving the equations. But at present, the analytical solution of this equations cannot be obtained, the research group carried out a lot of numerical analysis and calculation, and the results are shown in Table 1.

Table 1. Relationship between parallel PT number and neutral point voltage, resonant frequency

| Number of parallel PT | Neutral voltage amplitude | Ferroresonance type |
|-----------------------|---------------------------|---------------------|
| 1                     | 472.56V                   | No ferroresonance   |
| 2                     | 1486.48V                  | Third harmonic ferroresonance |
| 3                     | 2674.65V                  | Third harmonic ferroresonance |
| 4                     | 3954.32V                  | Third harmonic ferroresonance |

It can be seen from Table 1 that ferroresonance does not occur when there is only one PT. With the increase of the number of parallel PT, the equivalent $L$ of multi PTs parallel becomes smaller, and the condition of ferroresonance is $\omega_0 = \sqrt{V/LC}$, frequency doubling ferroresonance is more likely to occur.

2.1.3. Failure of primary and secondary ferroresonance elimination methods.
For a single PT system, the primary and secondary ferroresonance elimination methods can be equivalent to connect a resistor $R$ in series on the inductance $L$, and the ferroresonance can be suppressed by consuming ferroresonance energy, as shown in Figure 5. However, when the primary and secondary ferroresonance elimination methods are adopted for each parallel PT, the ferroresonance elimination resistance is approximately parallel, so the resistance $R$ in Figure 5 is reduced to $R'$, which weakens the inhibition effect on ferroresonance. If the number of PT in parallel is large, the primary and secondary ferroresonance elimination methods may fail.

![Figure 5. Equivalent circuit of series primary or secondary ferroresonance-constraining resistance](image)

2.2. Neutral point grounded through arc suppression coil
The grounding of neutral point by arc suppression coil is equivalent to parallel the inductance of arc suppression coil at PT. And its inductance is much smaller than the equivalent inductance of PT, it is equivalent to short the equivalent inductance of PT. The ferroresonance frequency of zero sequence loop depends on the inductance of arc suppression coil and the capacitance of line to ground, the parameter condition of ferroresonance is destroyed, and ferroresonance can be eliminated effectively.

When single-phase earth fault occurs, the short circuit current of the system becomes smaller due to the compensation of arc suppression coil, which is not conducive to single-phase earth fault location. Therefore, the neutral point grounded by arc suppression coil is not conducive to the safe operation of island microgrid.
2.3. Neutral point grounded by small resistance
The ferroresonance energy can be consumed when the neutral point is grounded through a small resistance. Because the grounding resistance is very small, the neutral point voltage can be clamped at a very small value to eliminate ferroresonance. A large number of practical operation experience shows that ferroresonance will not occur when the neutral point is grounded through a resistance of 10~20 Ω. Therefore, in this paper, after the microgrid enters the island mode, a neutral point grounded by the ferroresonance elimination resistance is put into quickly to provide a channel for the release of the charge. Even if there are several PTs in parallel in the system, the ferroresonance can still be effectively eliminated.

As shown in Figure 6, the auxiliary contact of grid connected breaker QF1 of microgrid is introduced into the controller, and the controller monitors the status of the auxiliary contact in real time. When the normally open contact of QF1 is detected to be open, the controller controls the circuit breaker QF2 to close, and the ferroresonance elimination grounding transformer and the ferroresonance elimination resistance are put into operation. In site actual, the control time is 200ms. The fast input of the ferroresonance elimination grounding transformer and the ferroresonance elimination resistor ensures the effective ferroresonance elimination.

3. Single-phase earth fault location technology
The topology of island microgrid with neutral point grounded by small resistance is shown in Figure 7. The system is composed of three inverter DGs, DG1 is V/f control mode, DG2 and DG3 are PQ control mode.

![Figure 6. Control circuit of ferroresonance-constraining resistance](image)

![Figure 7. Island microgrid topology](image)
When the single-phase earth short occurs at the fault point 1, the three sequence network is established by using the symmetrical component method, and the composite sequence network shown in Figure 8 is obtained. The zero sequence current of the system can be calculated according to Figure 8. $\dot{E}_1$ is the positive sequence network equivalent voltage source, $Z_{\Sigma}^+$ is the positive sequence equivalent impedance, $Z_{\Sigma}^-$ is the negative sequence equivalent impedance, $Z_{\Sigma}^0$ is the zero sequence equivalent impedance.

![Figure 8. Compound sequence network](image)

Due to the general angular connection mode of high voltage side winding of DG and load transformer, and PT angle type is open connection method with large excitation impedance, so the zero sequence current only flows between the short circuit point and the grounding transformer.

Set the starting value of zero sequence current to $I_{aviger}$. Set the detection point of detecting that the zero sequence current is greater than $I_{aviger}$ to 1, and the detection point of detecting that the zero sequence current is less than $I_{aviger}$ to 0. The fault point is located between two adjacent detection points with values of 1 and 0 on a certain line.

4. Simulation

In order to verify the correctness of the conclusion, the island microgrid as shown in Figure 7 is built by Matlab / Simulink. The microgrid is composed of three DGs, three PTs are connected in parallel, a ferroresonance elimination grounding transformer $T$ and a ferroresonance elimination resistor $R$, $R$ is 10 Ω.

4.1. Island microgrid before neutral point grounded by small resistance

When the breaker connected to the main network is disconnected, the system neutral point voltage is as follows:

![Figure 9. Neutral point voltage after being separate form the main network](image)

It can be seen from Figure 9 that when the neutral point of the main network is lost, the microgrid in island mode will have a third harmonic ferromagnetic resonance.
4.2. Neutral point grounded by small resistance

When \( t = 0.2 \) s, the microgrid is separated from the main network. When \( t = 0.4 \) s, 10Ω ferroresonance elimination resistor is put. The system neutral voltage is as follows.

![Figure 10. Neutral point voltage after using the ferroresonance-constraining resistance](image)

It can be seen from Figure 10 that the neutral point voltage is quickly restored to its normal value and the ferroresonance can be effectively eliminated by adopting this measure.

4.3. Single phase ground fault location

Set the starting value of zero sequence current as 10A. Phase A short circuit occurs at fault point 1 in 2s, and zero sequence current of all detection points is calculated. Only the zero sequence current of detection point 2 is greater than 10A, as shown in Figure 11.

![Figure 11. Zero sequence current of detection point 2](image)

Set the detection point with the detected zero sequence current greater than 10A to 1, and the detection point with the detected zero sequence current less than 10A to 0, then the values of all detection points are shown in Table 2.

| Detection point | 1 | 2 | 3 | 4 | 5 | 6 |
|----------------|---|---|---|---|---|---|
| Value          | 0 | 1 | 0 | 0 | 0 | 0 |

According to Table 2, the short circuit point is located between detection point 1 and detection point 2.

5. Conclusion

In view of the medium voltage island microgrid, three operation modes are analyzed respectively: the neutral point is ungrounded, the neutral point is grounded through arc suppression coil, and the neutral point is grounded through small resistance. For the ungrounded neutral system, ferroresonance is easy to occur because of the parallel connection of multiple PTs, and primary and secondary ferroresonance elimination resistors are unable to eliminate ferroresonance. At the same time, the small short circuit current is not conducive to fault location under this grounding mode. For the neutral point grounded by
arc suppression coil, although it can effectively eliminate the ferroresonance, the short circuit current of the system is small due to the compensation effect of arc suppression coil, which is also not conducive to fault location. For the system whose neutral point is grounded by a small resistance, the ferroresonance can be eliminated effectively, and the single-phase earth fault location can be realized by using the distribution characteristics of the zero sequence current of the system. Finally, the neutral point of medium voltage island microgrid is grounded by a small resistance, and the single-phase earth fault location technology based on zero sequence current distribution characteristics is proposed. The simulation results show that the proposed method is correct.

Acknowledgments
Fund project: Science and technology project of State Grid Liaoning Electric Power Co., Ltd.: Research on rapid disposal and state diagnosis technology of single phase grounding fault of distribution network lines (2020YF-02)

References
[1] FANG, L., NIU, Y.G., WANG, S.M. (2018) Optimal capacity determination method based on day-ahead scheduling and real-time control. Power System Protection and Control, 46: 102–110.
[2] LIU, Z.Y., XU, H.L., YANG, C.H. (2018) Research on the smooth switching control method of micro-grid with series combination of micro-source. Power System Protection and Control, 46: 151–155.
[3] LU, Y., ZHANG, W.C., ZHANG, X.C. (2016) Study on mechanisms of voltage instability in islanding grid after fault disconnection. Power System Protection and Control, 44: 81–86.
[4] WEI, H.J., ZHAO, W.J., LIU, X.S. (2016) Grounding systems of micro-grids and safety analysis. Water Resources and Power, 31: 212–215.
[5] ZHANG, H.D., YANG, X., WANG, H.B. (2015) Study on grounding arrangement of microgrid of city. Power System Protection and Control, 43: 137–142.
[6] MEI, C.L., ZHANG, C.S. (2008) Analysis of Voltage Transformer Ferroresonance. Power System Technology, 32: 311–313.
[7] JAZEBI S., FARAZMAND A., MURALI B.P. (2013) A Comparative Study on pi and T Equivalent Models for the Analysis of Transformer Ferroresonance. IEEE Transactions on Power Delivery, 28: 526-528.
[8] ZHOU, L.X., YIN, Z.D., ZHENG L. (2007) Research on Principle of PT Resonance in Distribution Power System and Its Suppression. Transactions of China Electrotechnical Society, 22: 153–158.
[9] HE, L.Z., WU, J.F., ZHANG L. (2018) Researches on Ferromagnetic Resonance Calculation and Harmonic Elimination Measures in Substation Based on EMTP-ATP. High Voltage Apparatus, 54: 210–216.
[10] GE, D., LU, T.C., WANG P. (2003) Study on Simulation Calculation of Ferroresonance Elimination in Power Distribution System. High Voltage Engineering, 29: 15–17.
[11] ZHANG, Y.S., LIU, S.B. (2016) Study of Comprehensive Suppression Method for Distribution Network Ferromagnetic Resonance. High Voltage Apparatus, 52: 137–142.
[12] YANG, Q.X., ZONG, W., TIAN, B.Y. (2001) DETECTION OF FERROMAGNETIC RESONANCE BASED ON WAVELET ANALYSIS. Power System Technology, 25: 55–57,61.
[13] LI, X.Y., DONG, X.Z., BO, Z.Q. (2011) DETECTION OF FERROMAGNETIC RESONANCE BASED ON WAVELET ANALYSIS. Power System Protection and Control, 39: 102–107.
[14] QI, Z., DONG, D., YANG, Y.H. (2010) Technique for Differentiation Between Ferroresonance and Single-phase-to-earth Fault in Isolated Neutral Point System. Automation of Electric Power Systems, 34: 55–58.