A new multilevel compensation system for neutral active grounding in distribution grid

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Abstract. In order to achieve effect of full compensation and zero residual-current, a multilevel compensation system for neutral point active grounding is proposed. The system is composed of three-level compensators. When power grid is grounded, the first level compensates its capacitive current, the second level compensates its active current, and the third level compensates not only its harmonic current, but also the harmonics generated by the former two level compensators, so effect of full compensation is very obvious. When distribution grid is in normal operation, the system uses the asymmetric voltage method to realize accurate detection of capacitive current and active current. In case of single-phase grounded fault, the harmonic current is extracted by fast Fourier algorithm. Then three-level compensators are quickly put into operation for corresponding compensation. A low-voltage simulated power grid is built in the laboratory, and a compensation test is carried out. The test results show that the compensation of capacitive current and harmonic current in grounding fault current is accurate. After further improvement, the system can reach the practical level.

1. Introduction

Due to historical reasons, neutral point of China’s distribution grid of medium-voltage is mostly resonant grounding, that is, grid connected to the arc-suppression coil to become compensation grid. When single-phase grounded fault occurs, arc-suppression coil outputs inductive current to compensate the capacitive current of power grid, so that residual current of grounding point is reduced to a lower level, which limits occurrence of arc grounded over-voltage and phase to phase short-circuit trip accident, so as to improve reliability of power supply and the safety of equipment operation. With expansion of urban power grid, an increase of power electronic load, and operation of a large number of cable lines, active and harmonic components of grounding residual current also increase significantly, which leads to increasing trend of phase to phase short circuit trip accidents. In recent years, wide using of arc-suppression coils belong to core coil type inductive structure, which can only output inductive current, but active current and harmonic current can not do anything [1,2]. In this way, the level of residual current is greatly improved, which easily leads to generation of arc grounded over-voltage, thus affecting the safe and reliable operation of distribution grid.

The best scheme to solve the above problems is to connect neutral point to active compensation devices, but most of these solving schemes are not targeted, which can not significantly reduce the
active and harmonic components of the grounding current, and their effect needs to be improved [3,4]. In order to solve the above problems, a multilevel compensation system for neutral active grounding is developed.

2. Design of multilevel compensation system for active grounding of neutral point

2.1. topology of multilevel compensation system with active neutral grounded

When single-phase grounding occurs, the grounding fault current of distribution grid \( i_g \) is composed of three parts, one is reactive component, which is mainly capacitive current \( i_c \) formed by line to ground capacitance, the other is active component \( i_r \), which is mainly formed by line to ground leakage resistance, and the last is harmonic component \( i_h \), formed by a large number of power electronic loads in grid, which is the grounding fault current \( i_g \), i.e., \( i_g = i_c + i_r + i_h \).

In order to effectively compensate these three components, a multilevel compensation system for neutral point active with three-level compensators are designed, as shown in Figure 1. The measurement and control device in the system measures and calculates the active current \( i_r \) and capacitive current \( i_c \) when distribution grid is in normal operation. When single-phase grounding occurs, harmonic current can be obtained by sampling and calculating quickly, and then the three-level compensators can be put into operation quickly in order to make the residual current close to zero and achieve effect of full compensation and zero residual current.

![Figure 1. Composition of multilevel compensation system for neutral active grounded.](attachment:image)

In figure 1, R is a limiting-voltage resistor. In order to ensure the maximum output of the three-level compensators under single-phase grounding fault, close K2 to exit it. TV is a voltage transformer connected in parallel between neutral point and ground to sample the asymmetric voltage of distribution grid, and TA is a current transformer connected in series with neutral point to sample current. K1 is a vacuum contactor, which can put the compensation system on or off [5]. The characteristics of this compensation system are described as follows.

Firstly, the three-level compensators are composed of single-phase full bridge inverter, which are all power electronic structure. Compared with the conventional arc-suppression coil with core-coil structure, they save a lot of copper and iron resources.

Secondly, the compensators consist of three levels, which can compensate capacitive current, active current and harmonic current respectively. As three independent slaves, the three-level compensators are controlled by the host of the measurement and control device. In this way, it has relative independence and is not affected by other compensators. At the same time, it can control residual current to a lower level by division of labor and cooperation, so as to realize full compensation and zero residual current.

Lastly, the whole control part adopts full digital master-slave structure. As the host, the measurement and control device completes detection of capacitive current and active current when
distribution grid is in normal operation, and completes detection of harmonic current when distribution grid is in grounded fault. As a slave, the main function of three-level compensator is to complete full compensation of fault current. One master and three slaves can be connected to the network conveniently through RS485 communication interface, and complete the functions of data transmission and control.

2.2. Design of multilevel compensation device

The multilevel compensation device is mainly composed of coupling transformer T and three-level compensators. The compensators are the core of the compensation device. Only one level compensator is shown in Figure 2. In addition, the design of the other two-level compensators is similar to it and will not be repeated.

2.2.1. Coupling transformer. The primary winding is connected to neutral point in series, and the secondary winding is divided into three windings to connect to the three-level compensators. The working voltage of the compensators connected to the secondary winding is low, and its operation is safe and reliable. At the same time, because of the low working voltage, its hardware cost is greatly reduced.

2.2.2. Three-level compensators. The core of the compensator is single-phase full bridge inverter circuit, and IPM power module is used in the design. The first level compensator compensates the fundamental component of grounding fault current, that is, capacitive current, with larger capacity; the second and third level compensators compensate the active component and harmonic component respectively, with smaller capacity. Each level of the compensator is composed of DSP, rectifier circuit and inverter circuit. As the slaves, they communicate with the measurement and control device and receive the data from the measurement and control device. According to these data, the CPU commands the inverter circuit in the compensator to output AC current with controllable phase angle, effective value and frequency. The DC power supply of the inverter circuit is provided by the three-phase rectifier circuit, and the rectifier bridge module is used in the design for convenience.

![Figure 2. Composition of output compensation system.](image)

3. Composition and measurement principle of the measurement and control device

3.1. Composition of the measurement and control device

The measurement and control device mainly realizes detection of neutral point voltage and current data in distribution grid, as well as the control of three-level compensators. As the control core of the system, measurement and control device plays a very important role in the whole system. The CPU of the measurement and control device is TMS320F28335, the sixth generation high-performance TMS320 series DSP of TI company. It is a 32-bit floating-point processor with fast running speed and can solve some problems of fast sampling and calculation of harmonics. The measurement and control device is mainly composed of forward channel, backward channel, man-machine interface circuit and communication interface circuit, as shown in Figure 3.
In Figure 3, the secondary windings of TV and TA, the small CT and PT installed in the measurement and control device, and the signal conditioning circuit constitute the forward channel, whose main function is to complete data acquisition of voltage and current. The backward channel is composed of driving circuit and vacuum contactors. The man-machine interface circuit includes LCD and keyboard interface, which is used for panel operation and data display. It is also a channel for the operator to contact with the system. The communication interface is composed of RS485 communication, and a master-slave half duplex communication network is established.

3.2. Measurement principle

Accurate measurement is the basis of accurate compensation, and the measurement principle is the necessary condition to ensure accurate measurement. In order to achieve the goal of zero residual current and full compensation, the measurement principle should be deeply studied. The measurement should include the detection of fundamental reactive power, active power and harmonic component of grounding current.

The measurement of capacitive current and active current is considered firstly. When distribution grid operates normally, its neutral point displacement voltage is lower than 15% of its phase voltage. At this time, K1 can be switched to measure the capacitive current and active current, which will not affect the operation of the distribution grid. Of course, in order to avoid sudden single-phase grounding and loss of compensation, the measurement action should be completed as soon as possible. It can be seen from Figure 1 that when K1 is disconnected, the neutral voltage collected by TV is the grid asymmetric voltage $E_0$. When K1 is closed, the grounding transformer, coupling transformer, line to ground capacitance, leakage resistance, etc. constitute the zero-sequence circuit, as shown in Figure 4. At this time, the zero-sequence current $I_0$ flows through TA. In the zero-sequence circuit, although the zero-sequence inductance $L_0$ of the grounding transformer and the leakage inductance $L_\sigma$ of the coupling transformer are very small, they still need to be included in the calculation for accurate measurement. $3g$ is the leakage conductance of three-phase line to ground, which is the main source of active component of zero-sequence current. $3C$ is the distributed capacitance of three-phase line to ground, which is the main source of reactive component of zero-sequence current [6].

![Figure 4. Zero-sequence equivalent circuit of distribution system under normal state.](image)

Let $L = L_0 + L_\sigma$, and leakage resistance of three phase line is $R_0 = \frac{1}{3g}$. The follow formulas can be obtained from figure 4.
\[
\frac{\dot{E}_0}{I_0} = R + \frac{R_0}{R_0 + \frac{1}{j\omega_3 C}} \frac{1}{j\omega_3 C} + j\omega L = R + \frac{R_0}{1 + (R_0\omega_3 C)^2} + j[\omega L - \frac{R_0^2\omega_3 C}{1 + (R_0\omega_3 C)^2}] \tag{1}
\]

\[
R + \frac{R_0}{1 + (R_0\omega_3 C)^2} = \text{Re}\left[\frac{\dot{E}_0}{I_0}\right] \tag{2}
\]

\[
\omega L - \frac{R_0^2\omega_3 C}{1 + (R_0\omega_3 C)^2} = \text{Im}\left[\frac{\dot{E}_0}{I_0}\right] \tag{3}
\]

The value of limiting resistance \( R \) is known, and \( L_0 \) and \( L_\sigma \) can also be measured at power frequency, so \( 3C \) and \( R_\theta \) can be obtained by (2) and (3), and the capacitive current and active current of the system can be obtained by (4) and (5) respectively.

\[
I_c = 3\omega C U_\phi \tag{4}
\]

\[
I_r = \frac{U_\phi}{R_0} \tag{5}
\]

In (4) and (5), \( U_\phi \) is phase-voltage of the grid.

The occurrence of grounding fault in distribution network is random and complex. When grounding fault occurs at different time and different places, the harmonic current generated in the zero-sequence circuit of distribution grid is very different, so it is not meaningful to detect harmonic current before grounding fault. The solution is that the multilevel compensators do not act at the moment of grounding fault. After the TA collects zero-sequence current, the system takes out and calculates the harmonic component from it by using FFT algorithm. Then, the first and second level compensators are switched on to compensate the capacitance current and the active current, and the third level compensator is switched on to compensate the harmonic component of grounded current and the harmonic current generated by the former two-level compensators. This method not only makes the grounded current of distribution grid all compensated, but also the harmonic current generated by the former two-level compensators compensated. As for the harmonic generated by the third level compensator, several sets of LC passive filters can be used to filter out.

After single-phase grounding occurs, in order to put compensators into operation as soon as possible, it is particularly important to improve the speed of fast Fourier algorithm. When the system designed, both hardware and software are considered comprehensively. In hardware, DSP with fast operation speed is selected. In software, because the grounding fault current belongs to one-dimensional signal, it can be extended to two-dimensional space, and the corresponding harmonics can be calculated by orthogonal method, which can speed up the detection speed and shorten the sampling time [7]. At the same time, for the fundamental current has been measured when distribution grid is in normal operation, only the harmonic components need to be sampled and calculated under grounding fault, so the calculation time is shorter.

3.3. Software design of multilevel compensation system for neutral active grounding

After the hardware design and measurement principle of the neutral active grounding multilevel compensation system are determined, the corresponding software is compiled for debugging. The main program of compensation system is more important, and its flow chart is shown in Figure 5.
4. The experiment in simulation low-voltage grid

After the development of multilevel compensation system for neutral point active grounding, a low-voltage simulation power grid is built in the laboratory, and the compensation experiment is carried out. The same effect can be achieved by replacing the distributed capacitance of line to ground with capacitors with centralized parameters and simulating single-phase ground fault with the input of circuit breaker with one end grounded.

In the experiment, the maximum input DC voltage of the multilevel compensator is 300V and the maximum working current is 30A. The three-level compensators generate the compensation current of fundamental, fifth harmonic and seventh harmonic respectively. The oscilloscope is connected to the three windings of the coupling transformer to measure the output voltage waveform and the corresponding PWM waveform, as shown in figure 6~8. Considering that the proportion of fundamental, fifth and seventh harmonics in grounding fault current is very large, it is necessary to focus on compensation. However, due to the short line and small leakage conductance, the active current of low-voltage simulation power grid is also very small, so the corresponding compensation output is not considered in the simulation test.

Figure 5. Diagram of main program for the system.

Figure 6. Fundamental waveform and PWM waveform output.

Figure 7. Fifth harmonic waveform and PWM waveform output.
Figure 8. Seventh harmonic waveform and PWM waveform output.

From the above compensation current waveform, some conclusions can be obtained that the three-level compensators can output the fundamental wave required by the distribution grid and the 5th and 7th harmonics with a large proportion. The third level compensator can also compensate the harmonics produced by the former two compensators, so the compensation effect is very significant. It can be also seen that the three-level compensation system is a perfect design to realize full compensation and zero residual current of single-phase ground fault in distribution grid.

5. Conclusion

In order to realize the effect of single-phase grounding full compensation and zero residual current in distribution grid, a new multilevel compensation system for neutral point active grounding is designed. The system is composed of three-level compensators, which respectively compensate capacitive current, active current and harmonic current in grounding fault current. At the same time, the last level compensator also compensates the harmonics generated by the former two-level compensators. The effect of full compensation is very significant. The measurement and control device in the system can realize accurate measurement of capacitive current and active current by using asymmetric voltage method. The harmonic current can be obtained by fast Fourier algorithm after single-phase ground fault. The software and hardware design of the system are given. The simulation test grid is set up in the laboratory, and the test results show that the compensation effect of the system on the fundamental reactive power component and harmonic component is satisfactory. In the future, it can reach the practical level through continuous improvement.

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