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Adaptability evaluation of relay protection in a GFM inverter system

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ABSTRACT

This paper introduces typical Grid-Forming (GFM) technologies in power grids, including steady-state and fault current limiting strategies, studies the equivalent structures of steady-state and fault traversal under GFM technology, analyses electrical characteristics under different fault types from the voltage plane, and illustrates the differences from traditional synchronous systems. This paper analyses the phase current differential protection, zero sequence current differential protection, and positive sequence voltage polarisation distance protection applied in traditional power grids, and clarifies their action behaviour under the GFM system. The analysis shows that the GFM technology creates a relatively good operating environment for relay protection by simulating the basic characteristics of synchronous generators, which is conducive to improving the operational performance of relay protection.

KEYWORDS GFM inverter; electrical characteristics; fault ride through; differential protection; distance protection
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1. Introduction

In order to achieve the goal of carbon neutrality, the application of a high proportion of renewable energy and high proportion of power electronic equipment is the main feature of the new power system. The power system will be transformed into a new type of system that is cleaner, more efficient, flexible and controllable.

With the access of new energy sources and the continuous withdrawal of synchronous machines, the decline in system short-circuit level has caused a series of problems such as the reduction in voltage stability margin, weak system-wide frequency oscillation, and abnormal relay protection action. Unlike the Grid-Following (GFL) technology, Grid-Forming (GFM) technology uses a synchronisation strategy similar to that of synchronous generators (Ma et al., 2023; Rakhshani et al., 2014; Rosso et al., 2021; Shim et al., 2019; Zhan et al., 2023; Zhong and Weiss, 2011). It does not rely on phase locked loops to achieve synchronisation with the system, effectively improving the stability of new power systems, and providing a new solution for building stable and highly reliable systems.

Due to the overload capacity of semiconductor devices, the GFM strategy still requires current limiting control during fault traversal, while synchronous generators can withstand short-term overcurrent capacity of six to seven times. Therefore, the dynamic response of the GFM strategy during fault traversal is still significantly different from traditional synchronous machine systems. It is necessary to analyse and evaluate the operational performance of relay protection. In recent years, scholars have proposed various types of GFM strategy, and most of them have focused on the realisation of the control objectives under steady-state conditions and system stability. However, the research on the adaptability of relay protection is rarely involved.

From the perspective of relay protection design, this paper analyses the equivalent system structure of a typical GFM strategy, and studies the differences in electrical characteristics under the GFM strategy and traditional synchronous machine systems during fault traversal. On this basis, the adaptability of the current typical functional configuration of transmission line relay protection is evaluated.

2. Principle of a typical GFM strategy

2.1. Control strategy for steady state

The GFM strategy mainly simulates the power generation characteristics and synchronisation mechanism of synchronous generators to achieve self-synchronisation functions, and outputs a given voltage amplitude and phase. Common GFM strategies include synchronous power control, droop control (Zheng et al., 2015), improved droop control, virtual synchronous machine control (Catalin et al., 2017; Zhong and Weiss, 2011), and virtual oscillator control.

There are differences in the specific implementation details of the control architecture of GFM strategies, but these strategies are expected to be close to the characteristics of traditional synchronous motors. Therefore, under steady state operation or small disturbance conditions, the external characteristics of the GFM strategy are similar to the synchronous machine, mainly including the following two typical characteristics: (a) The converter presents a voltage source externally; and (b) Synchronisation is achieved by controlling the output power (or DC voltage) of the converter itself.

The typical control block diagram of the GFM inverter system (Wang, 2022) analysed in this article is shown in Figure 1:

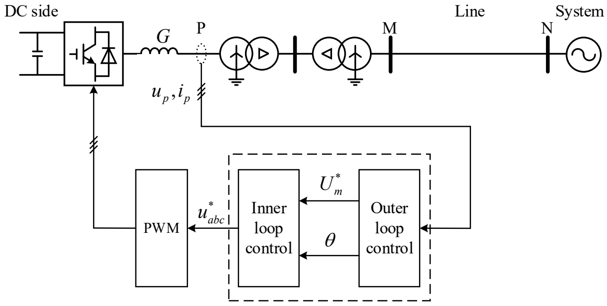

Figure 1. Typical control block diagram of GFM.

In Figure 1, u_p and i_p are, respectively, the voltage and current at the grid side of the inverter. It is specified that the inverter points to the grid side in the positive direction of the current; u is the inverter port voltage; U^*_m is the reference voltage amplitude; θ is the voltage phase given value; u_{abc} is a three-phase voltage modulation wave. A GFM inverter system generates a given amplitude signal (U^*_m) and phase signal (θ) of the voltage based on the outer loop power control link by collecting the voltage and electrical flow at the junction point (P), and then outputs a modulation signal through the inner loop voltage and current control link. The PWM generator ultimately generates a drive signal for the semiconductor switching device. After filtering high-frequency harmonics through the filter inductor G, the inverter is connected to the AC power grid at the common coupling point P to achieve closed-loop operation of the control system.

Currently, the commonly used strategies such as droop control and virtual synchronous machine control form the self-generated voltage phase, while the reactive power control link forms the self-generated voltage amplitude. Under steady-state operation, the converter port voltage amplitude and phase are considered to be able to simulate the basic characteristics of the generator, and their external characteristics can be equivalent to a single voltage source.

2.2. Control strategy for fault traversal

Due to the limitation of the overcurrent capacity of the inverter, it is still necessary to limit the output current of the inverter during a low voltage ride through (LVRT) after adopting the GFM strategy; otherwise, damage to the device may occur. This paper mainly analyses and studies the electrical characteristics and their impact on protection during transient periods under large disturbances such as system faults.

Currently, there are two main types of fault current limiting algorithms commonly used:

(a) Direct current limiting (Lin et al., 2021). The direct current limiting methods are generally divided into two categories: The first stage is that the GFM strategy is still used when overcurrent occurs, and the current reference value needs to be limited. The inner loop controller achieves accurate tracking of current instructions, also known as current saturation control; the second stage is to switch to traditional PLL-based vector control when overcurrent occurs, and achieve current limiting by accurately controlling the current. The method of direct current limiting is fast and accurate, but during the limiting period, the characteristics of the flexible and direct voltage source are converted to the characteristics of the current source.

(b) Indirect limiting (Li et al., 2022; Wu and Wang, 2022). Indirect amplitude limiting is achieved by controlling and increasing the internal virtual impedance, which is essentially equivalent to increasing the electrical distance between the inverter and the fault point. During current limiting processing, the virtual impedance can increase smoothly, and the external characteristics during a fault appear to be the characteristics of voltage source series adjustable impedance.

When using the direct current limiting mode, the voltage source characteristic of the inverter will be switched to the current source characteristic, and the stability margin will be greatly reduced. Therefore, the analysis object of this article is to adopt an indirect current limiting control strategy.

The virtual impedance current limiting method can be intuitively understood as introducing a control link containing virtual impedance in the existing voltage and current inner loop control link. The control block diagram is shown in Figure 2:

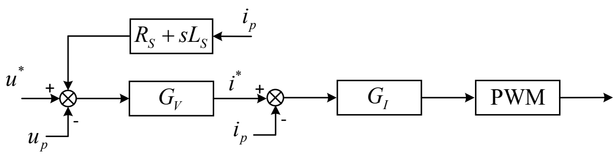

Figure 2. Diagram of voltage and current inner loop control with virtual impedance.

The indirect amplitude limiting method of virtual impedance current limiting introduces an adjustable virtual impedance value to reduce the overcurrent problem during grid faults, and changes the equivalent system impedance between the potential in the inverter and the junction point P. This system impedance value is equal to the parameter introduced in the control link. Under steady-state operation, this parameter can generally be set as the corresponding parameter of the filter inductance, reported below for simplicity:

$$R_S + jX_S = jX_G \,. \qquad (1)$$

In the case of a system fault, depending on the degree of voltage sag, the effect of current limiting can be considered to be inversely proportional to the degree of voltage sag, which can be equivalent to adding an additional virtual impedance to the existing filter inductance, namely:

$$R_S + jX_S = jX_G + R_V + jX_V \,. \tag{2}$$

In order to effectively improve the short circuit ratio of the system and enhance the overall operational stability, the current limiting control strategy design of the current structured converter aims to fully utilise the overload capacity of the device. The allowable overcurrent capacity of the GFM inverter system during a fault can generally reach above 1.5 times the rated current.

2.3 Stability analysis based on GFM technology

Compared with GFL converters, one of the advantages of the GFM strategy is that it has good stability when connected to weak networks. GFM strategy converters can adapt to access low short circuit ratio (SCR) systems. Taking the current typical virtual synchronous machine control strategy as an example, the active power control adopts the following control strategy:

$$\begin{cases} P_{ref} - P_e = J\dfrac{d\omega_d}{dt} + k_d(\omega_d - \omega_0) \\ \delta_d = \int \omega_d dt \end{cases} . \tag{3}$$

J is the rotor inertia coefficient, and k_d is the damping coefficient.

The inertia coefficient and damping coefficient of the GFM-type inverter are directly set in the control process, rather than being determined by multiple variables like in GFL-type control. Therefore, the GFM-type inverter has better performance under large disturbances.

From the perspective of equivalent impedance, there are mainly the following conclusions regarding the system stability of GFM-type inverters:

(a) In terms of device selection, the allowable current withstand capacity of the GFM-type inverter is generally higher than that of the GFL type, in order to leverage its equivalent synchronous machine characteristics, with a short-circuit current of 2-3 p.u.;

(b) When there is no local load, the SCR of the system that can be connected to the GFM-type power supply transmission system needs to be slightly greater than 1; and

(c) Under the presence of local or adjacent loads, the GFM-type inverter can operate with SCR<1. When operating on an isolated island, i.e., SCR=0, the corresponding system impedance is infinite.

3. Electrical characteristics of GFM

3.1. Equivalent circuit of the GFM strategy

Taking the system shown in Figure 1 as an example, the equivalent system structure of GFM under steady-state operation can be described as shown in the following figure:

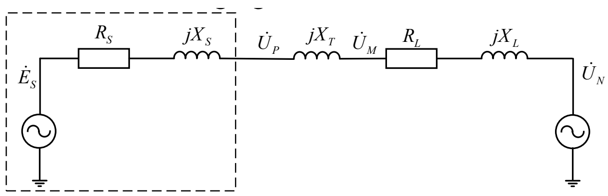

Figure 3. Structure diagram of an equivalent system.

According to the description of the additional virtual impedance in the above, the expression corresponding to the voltage phasor at the junction point is:

$$\dot{U}_P = \dot{E}_S - \dot{I}_P(R_S + jX_S) \,. \tag{4}$$

Under steady-state operation:

$$\dot{U}_P = \dot{E}_S - \dot{I}_P(R_S + jX_S) = \dot{E}_S - \dot{I}_P(jX_G) \,. \tag{5}$$

Under symmetrical faults:

$$\dot{U}_P = \dot{E}_S - \dot{I}_P(R_S + jX_S) = \dot{E}_S - \dot{I}_P(R_V + j(X_G + X_V)) \,. \tag{6}$$

For a synchronous generator, within the time of relay protection analysis, it can be equivalent to the internal potential and impedance, while for a GFM inverter system, due to the introduction of virtual impedance during a fault, it is equivalent to the effect that the internal potential is constant, but the system impedance changes according to the design parameters.

3.2. Phasor characteristics of different fault types

3.2.1. Simplified system structure

Assuming that a GFM inverter is connected to a synchronous machine system through a transmission line, the synchronous machine system is equivalent to a constant potential before and after a fault, and the system impedance is constant. The virtual impedance introduced by the GFM inverter during fault traversal is generally dominated by the reactance component. To simplify the analysis, ignoring the resistance component in the overall system, the electrical characteristics of the fault at the protection installation under different fault types are analysed separately.

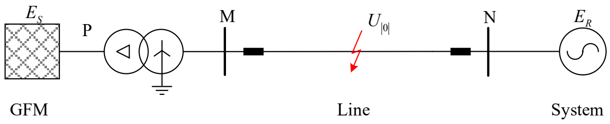

Figure 4. Transmission system with a GFM inverter system.

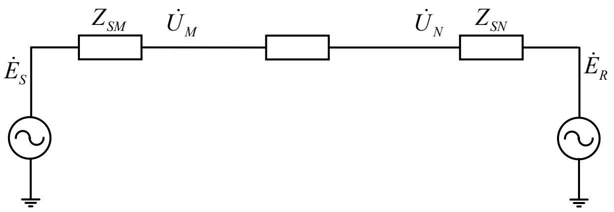

Figure 5. Equivalent diagram of system and line.

3.2.2. Phasor characteristics of steady state operation

Under steady-state operation, the equivalent system impedance of the GFM inverter side is mainly determined by the filter inductance parameters. To ensure power transmission and maintain system stability under disturbance conditions, the angle between the internal potential of the GFM side and the internal potential of the opposite side system must be less than 90 degrees. The voltage phasor characteristics at different positions of the system are shown in the following figure:

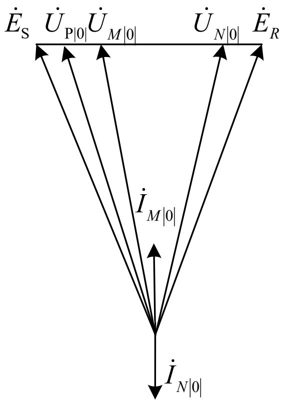

Figure 6. Voltage and current phasor diagram during steady-state operation.

Since the GFM inverter is equivalent to a constant potential in series with a filter inductor, it can be seen from the voltage phasor plane that the steady-state electrical characteristics of the system are not significantly different from traditional synchronous machines. The potential difference between the systems on both sides is within the normal operating range.

3.2.3. Phasor characteristics of symmetrical faults

When a symmetrical fault occurs on a transmission line, for the M-side protection installation point, the GFM inverter does not need to lock the system potential phase by building its own internal potential. Therefore, although the M-side system loses contact with the opposite power grid, it is still able to maintain a constant internal potential, while judging the voltage drop situation by introducing a virtual impedance to reduce the system fault current.

From the voltage phasor plane, the voltage and current characteristics at different positions of the system after a fault are plotted as follows:

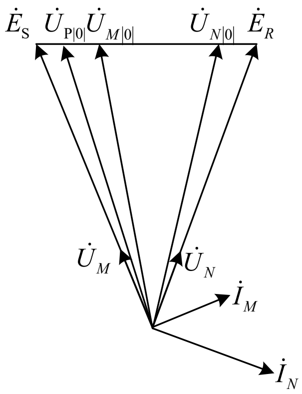

Figure 7. Voltage and current phasor diagram of symmetrical faults.

According to the generally allowable 1.5 p.u. overcurrent capacity of a GFM inverter, the short-circuit current after a fault is about 1.5 times the load current under a full load. In the case of a symmetrical fault, the systems on both sides are completely isolated, and the characteristics of the current amount after the fault are independent of the load state before the fault. The voltage at the protection installation on both sides is the same as the potential phase in the system that provides the fault current. The current at the side protection installation of the GFM inverter lags behind the potential in the system by about 90 degrees, and the current is about 1.5 p.u.; The current at the installation of the system side protection lags behind the potential in the system by about 90 degrees, and the current amplitude depends on the equivalent impedance on the system side.

3.2.4. Phasor characteristics of asymmetrical faults

This section takes single-phase faults as an example to analyse the electrical characteristics under fault conditions. Other fault types can be analogised to obtain corresponding conclusions.

Single-phase faults cause port voltage drops, and the GFM inverter uses virtual impedance to achieve indirect current limiting. Current virtual impedance current limiting measures can achieve the introduction of equal positive and negative sequence virtual impedances, which is conducive to the analysis of fault electrical characteristics.

Based on Thevenin's theorem, the composite sequence network diagram of the fault port for a single-phase fault is shown below.

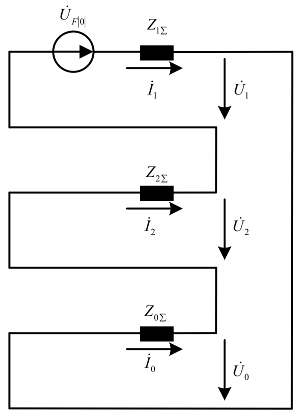

Figure 8. Sequence diagram of a failure point.

$Z_{1\Sigma}$, $Z_{2\Sigma}$ and $Z_{0\Sigma}$ are the equivalent impedances seen from the fault port, where $U_{F|0|}$ is the open circuit voltages corresponding to the fault point. Due to the changes in the equivalent system impedance of the GFM inverter after a fault, it is not possible to directly use the load state for calculation. Instead, the equivalent virtual impedance of the GFM inverter after the fault should be used to form the open circuit voltage. The specific voltage phasor situation is shown in the figure. The voltage is not equal to the potential at the fault point before the fault, and its phase is closer to the potential of the N side.

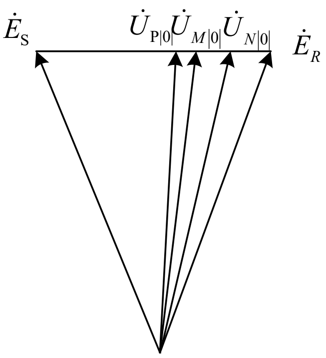

Figure 9. Open circuit voltage phasor at a fault point.

Based on the composite sequence network diagram, the positive sequence voltage at the fault point after a fault can be calculated as follows:

$$\dot{U}_1 = \frac{Z_{2\Sigma} + Z_{0\Sigma}}{Z_{1\Sigma} + Z_{2\Sigma} + Z_{0\Sigma}} \dot{U}_{F|0|} \quad (7)$$

According to the impedance control effect of the GFM inverter, the impedance in the above formula can be considered to be dominated by the reactance component, so the positive sequence voltage $\dot{U}_{F1}$ is close to the phase of $\dot{U}_{F|0|}$, and the amplitude is close to $1/2\dot{U}_{F|0|}$ due to the small zero sequence impedance. The positive sequence voltage phasor at the protection installation is located between the internal potential $\dot{E}_s$ and $\dot{U}_{F1}$. The difference between the positive sequence voltage ($\dot{U}_{F1}$) at the post fault protection installation and the equivalent internal potential of the GFM inverter ($\dot{E}_s$) is small, and this characteristic is basically similar to that of traditional power grids.

The GFM strategy, through virtual impedance control, can reduce the short circuit current of the system, and effectively reduce the phase change of the positive sequence voltage after a fault, providing a reference vector for protection calculation.

The voltage and current characteristics are plotted on the voltage phasor plane. From the voltage plane view, the electrical quantities conform to the following relative relationships:

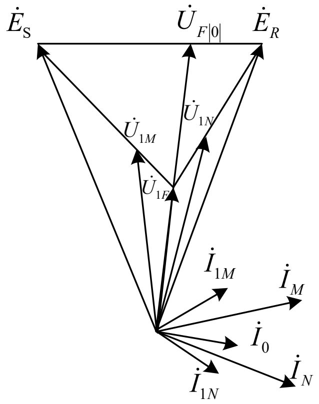

Figure 10. Voltage and current phasor diagram of a single-phase to ground fault.

4. Adaptability evaluation of relay protection

This section takes a single-phase fault as an example to analyse the operational characteristics of different types of protection in the GFM system.

4.1. Characteristics of differential protection

Transmission line differential protection applied in power grids mainly includes the following two types:

(a) Steady-state current differential element

The calculation of the steady-state restraint current and differential current is phase-segregated,

$$\begin{cases} I_{\mathrm{D}\varphi} > 0.6 I_{\mathrm{R}\varphi} \\ I_{\mathrm{D}\varphi} > I_{\mathrm{mk}} \\ I_{\mathrm{D}\varphi} = |\dot{I}_{\mathrm{M}\varphi} + \dot{I}_{\mathrm{N}\varphi}| \\ I_{\mathrm{R}\varphi} = |\dot{I}_{\mathrm{M}\varphi} - \dot{I}_{\mathrm{N}\varphi}| \end{cases}, \quad (8)$$

where:
$I_{D\varphi}$: The phase differential current;
$I_{R\varphi}$: The phase restraint current;
I_{mk} : The differential action threshold.
The operation coefficient is 0.6.

The phase difference current reflects the current at the fault point. From the fault sequence network diagram above, it can be inferred that the fault current lags behind the open circuit voltage at the fault point by about 90 degrees, and the fault current is large, which can meet the action threshold.

The key factor determining whether the operation coefficient can be satisfied is the angle relationship between the positive sequence current and the negative sequence (zero sequence) current. From the phasor diagram, it can be seen that due to the influence of the load current, the positive sequence current is ahead of the negative sequence current. Considering that the power angle difference between the systems on both sides is less than 60 degrees, in general, the leading amount is less than 45 degrees. From this, it can be inferred that the phase angle difference between the fault currents on both sides is less than 45 degrees, so the operation coefficient can be satisfied when there is an internal fault in the line.

(b) Neutral current differential element

For a high-impedance fault which changes slowly under heavy load conditions, the sensitivities of the steady-state differential current element cannot meet the requirement, so the device provides a neutral current differential element using a zero sequence current.

Its criterion is:

$$\begin{cases} I_{\mathrm{D0}} > 0.75 I_{\mathrm{R0}} \\ I_{\mathrm{D0}} > I_{\mathrm{mk0}} \\ I_{\mathrm{D0}} = |\dot{I}_{\mathrm{M0}} + \dot{I}_{\mathrm{N0}}| \\ I_{\mathrm{R0}} = |\dot{I}_{\mathrm{M0}} - \dot{I}_{\mathrm{N0}}| \end{cases}, \quad (9)$$

where:
I_{D0} : The zero sequence differential current;
I_{R0} : The zero sequence restraint current;
I_{mk0} : The zero sequence differential action threshold.
The operation coefficient is 0.75.

Depending on the zero sequence impedance characteristics of the transformer, the zero sequence circuit is not affected by the power electronic control characteristics. When there is an internal fault in the line, the zero sequence current direction on both sides is basically the same, and the braking coefficient of the zero-difference protection for the fault in the zone can meet the requirements. In addition, the system can provide a sufficient short-circuit current, so the zero sequence differential current should meet the action threshold.

4.2. Characteristics of distance protection

For a forward direction or reverse direction close-up fault, the voltage of the faulty phase is almost 0, and the measured impedance of the faulty phase is located in the origin of the R-X plane. A positive sequence voltage is used as polarised voltage to distinguish between a forward direction fault and a reverse direction fault.

The phase comparison equation of the forward direction distance element and reverse direction distance element is:

$$-90^{\circ} \le Arg\frac{\dot{U}_{OP\phi}}{\dot{U}_{P\phi}} \le 90^{\circ}, \quad (10)$$

where:
$\dot{U}_{P\phi}$ is the polarised positive sequence voltage, i.e.,
$\dot{U}_{P\phi} = -\dot{U}_{1\phi}$
$\dot{U}_{OP\phi}$ is the operating voltage.

For the phase-to-ground distance element, taking phase-A as an example:

$$\dot{U}_{OPA} = \dot{U}_{A} - (\dot{I}_{A} + k \times 3\dot{I}_{0}) \times Z_{set}. \quad (11)$$

The operating characteristics of a distance relay with positive sequence voltage polarisation are based on the fact that the positive sequence voltage in traditional systems can reflect the phase of the system potential that provides a fault current, thereby simplifying the operating equation and having good directionality.

Based on the above analysis, the equivalent potential of the GFM inverter is constant, and its characteristics can maintain a small deviation between the positive sequence voltage at the protection installation and the system potential. It can be inferred that when the GFM inverter has a fault in the positive direction and the converter provides a fault current, the positive sequence voltage polarisation distance relay has good operating characteristics.

4.3. Brief summary

In a GFM inverter system, due to the constraints of the potential on both sides during a fault, the angle difference between the fault currents on both sides is less than 90 degrees, so the braking characteristics of the phase current differential protection can be met, while the braking characteristics of the zero sequence current differential protection are not affected by the power electronic control strategy. Overall, the differential protection action characteristics are relatively similar to the behaviour of traditional weak power systems, and the action performance can meet the engineering requirements.

In a GFM inverter system, due to its ability to maintain a constant system potential and its equivalent additional impedance exhibiting reactance characteristics, it is ensured that the positive sequence voltages at different locations in the system are substantially similar to the direction of the potential providing the fault current in the event of a line fault, enabling the protection device to obtain reliable potential references as polarisation values for the construction of distance relays, effectively improving the operational performance of distance protection.

5. Conclusion

This paper studies the electrical characteristics of the GFM inverter system under different operating conditions, and evaluates the adaptability of various types of relay protection. The main conclusions are as follows:

(a) The GFM inverter introduces a virtual impedance-based indirect current limiting method, and its control effect can reach the form of a voltage source series variable reactance within the relay protection analysis time window;

(b) Under symmetrical faults, the GFM inverter can maintain the relative relationship between the output current and voltage, and the phase relationship between fault currents on both sides is similar to that of traditional synchronous machine systems;

(c) In the case of asymmetric faults, the positive sequence voltage at the protection installation is close to the potential phase of the systems on both sides, which means that the positive sequence voltage can represent the potential phase that provides the fault current, and the fault circuit mainly presents reactance characteristics;

(d) In a GFM control system, the operation coefficient of the phase current differential protection can be satisfied, and the zero sequence current differential protection is not affected by the power electronic control effect; and

(e) The distance relay with positive sequence voltage polarisation has good protective action performance in a GFM control system.

Overall, the GFM strategy can simulate the output characteristics of the synchronous machine, providing a relatively friendly operating environment for relay protection devices, and ensuring the overall operational performance of relay protection.

In response to the development of new power systems, there are many ways to improve the performance by utilising dual terminal information as the main protection. However, for protection using single-terminal information, especially the distance protection function, it is greatly affected by the connection of different types of converters. In the next step of work, further expansion research will be conducted on distance protection, mainly including:

(a) Standardising the grid connection code of inverters to achieve consistency in external features;

(b) Utilising transient auxiliary feature information, combined with sampling value distance and other means, to achieve fault identification; and

(c) Establishing communication channels, identifying the operating status of the inverter, and flexibly adjusting the range of distance protection actions.

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