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Method of Harmonic Differential Protection for PV Grid-Connected Loads Based on Characteristic Signal Injection

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Abstract: With the rapid development of photovoltaic (PV) power generation technology, especially the widespread application of inverter-interfaced distributed generation (IIDG), its impact on distribution networks has become increasingly significant. To fully utilize the positive effects brought by IIDG integration into distribution networks, this paper proposes a method of harmonic differential protection for PV grid-connected loads based on characteristic signal injection. This method achieves effective protection of system load components by adding a characteristic signal injection strategy to the current inner-loop controller of inverters. Through theoretical analysis and simulation verification, the effectiveness of this method under different fault conditions is proven.

1. Introduction

In recent years, with the advancement of renewable energy technologies and enhanced environmental awareness, particularly photovoltaic (PV) inverter-type distributed generation (IIDG) has been widely applied. However, the integration of IIDG into traditional distribution networks presents new challenges, especially in relay protection. Traditional protection methods struggle to adapt to the dynamic characteristics of IIDG, potentially leading to misoperation or failure, thus affecting the safe and stable operation of the system. Therefore, how to effectively utilize the active participation characteristics of IIDG to improve the protection performance of distribution networks has become a current research hot spot.[2]

This paper aims to explore a harmonic differential protection method based on characteristic signal injection to protect the load end of the distribution network, addressing the aforementioned issues. This method introduces a characteristic signal injection strategy into the current inner-loop controller of inverters, making the relay protection action characteristics more flexible. First, the paper analyzes the generation of characteristic signals and their implementation in inverter control; second, it discusses the selection of characteristic signals, including frequency, length, and amplitude determination; finally, it proposes a harmonic differential protection scheme based on characteristic signal injection and verifies its effectiveness and feasibility through simulations.[3]

This study not only provides a new solution for the protection problems caused by IIDG integration into distribution networks but also lays a theoretical foundation for the future development of intelligent distribution networks.

2. Characteristic Signal Injection Strategy

2.1 Injection of Characteristic Signals

As shown in Figure 1, which depicts the inverter control block diagram containing characteristic signal injection, an additional control strategy for injecting characteristic signals is added to the current inner-loop controller. The harmonic injection module works in conjunction with the control loop of the distributed power source without affecting its own control loop, making it adaptable to various types of distributed power sources.[8] During faults, actively injecting characteristic signals makes fault features more prominent and easier to detect, enabling subsequent fault detection and protection coordination. This scheme is suitable for micro-grids with high penetration rates of IIDG. In cases where IIDG exits operation, backup protection schemes such as inverse-time over-current protection can be configured.[4]

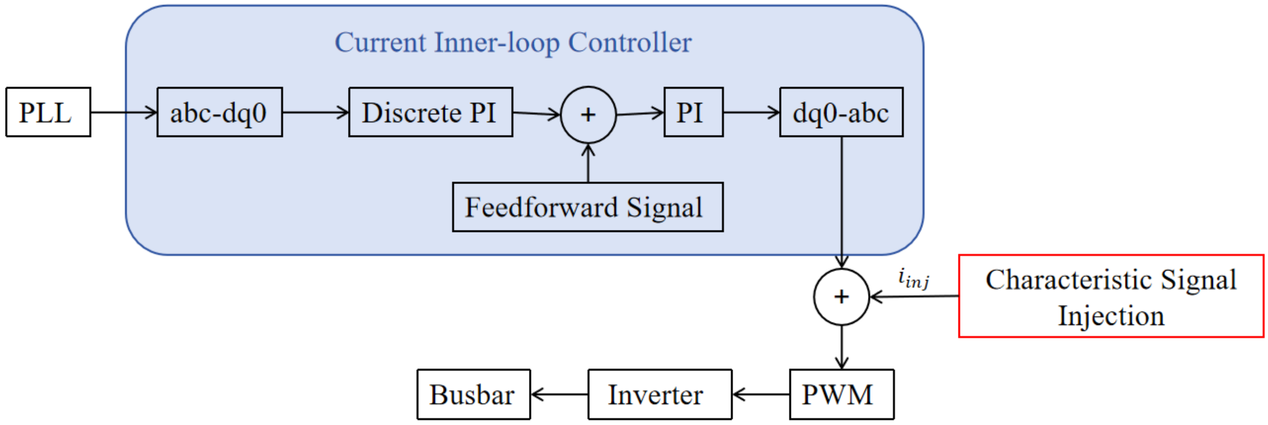


Figure 1. Control Block Diagram of Inverter with Active Characteristic Signal Injection

For micro-grids containing IIDG, there are harmonic content limits during normal operation. Higher harmonics have stricter limits. If IIDG control modules inject high-order harmonic energy after a fault, due to the low amplitude of high-order harmonics generated by the micro-grid itself, the injected high-order harmonic energy is easily identifiable.

The conventional control modules of IIDG generally include power/voltage outer-loop control modules, current inner-loop control modules, current-limiting modules, pulse-width modulation (PWM) modules, and filtering modules. Conventional control modules determine the control mode of IIDG, such as PQ or V/F control.[6]

In this chapter, characteristic signals are injected before the modulation signal generated by the conventional control loop is fed into the PWM module, as shown in Figure 1. Here, i_{inj} represents the injected harmonic current. The harmonic injection module and the conventional control module are relatively independent, sharing no other common control variables except for the output voltage and current of IIDG, thereby minimizing mutual influence.

The expression for the injected harmonic energy is:

$$i_{inj}(t) = \sqrt{2} I_n^{inj} \sin(\omega_n t + \beta_n) \tag{1}$$

$$\omega_n = 2\pi f_n = \frac{2\pi}{T_n} \quad (2)$$

ω_n, f_n, T_n represent the angular frequency, frequency, and period of the nth IIDG injected characteristic signal; β_n is the initial phase angle of the harmonic component; I_n^{inj} is the RMS value of the injected characteristic signal current. Using this control method, fault currents contain a certain proportion of harmonics.

The selected characteristic signal for injection is a high-order harmonic, and its RMS value is proportional to the RMS value of the IIDG output current.

$$I^{inj} = \lambda I^{DG} \quad (3)$$

$$HI_x = \frac{I_x}{I_1} \times 100\% \quad (4)$$

where I^{DG} is the harmonic content rate, HI_x is the RMS value of the IIDG output current, I_1 is the fundamental current content, and I_x is the harmonic current content. Since high-order harmonic signals are chosen for injection, the Fast Fourier Transform (FFT) is used for data collection.

2.2 Selection of Characteristic Signals

(1) Frequency of Injected Signals

Since the characteristic signal injection occurs before the PWM module, the harmonic energy frequency must be less than the cutoff frequency of the filter to avoid resonance and attenuation. Considering the cost of subsequent detection technology, excessively high-order harmonics should be avoided.[5]

(2) Length of Injected Signals

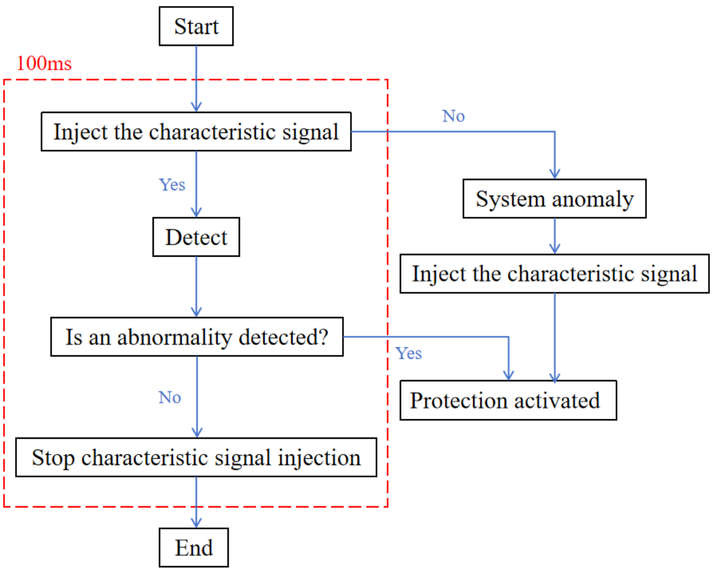


Figure 2. Flowchart of Characteristic Signal Injection.

To ensure system stability and maintain power quality, characteristic signals cannot be continuously injected but should be intermittently injected. To ensure accurate signal detection and reliable protection judgments, the injected characteristic signal needs to have a certain length.

Considering communication delays and data processing time margins, each distributed power source injects the characteristic signal for 100 ms, equivalent to two fundamental cycles. The gap between injections should not be too short to avoid affecting the grid's voltage, current, and power, but it should not be too long to ensure timely fault recognition. Normally, signals are injected once per second. If no anomaly is detected within 100 ms, the injection stops. If an anomaly is detected within 100 ms, continuous injection continues until protective actions occur. If an anomaly is detected during the non-injection period, immediate signal injection starts until the anomaly is resolved.[7] The process of characteristic signal injection is illustrated in Figure 2.

(3) Amplitude of Injected Signals

If the amplitude of the injected harmonic energy is too small, it increases the difficulty of identification and detection, preventing accurate information extraction. If the amplitude is too large, it causes excessive disturbances in the grid, negatively impacting power quality. Moreover, large amplitudes need to consider the capacity of various power electronic devices. To identify fault regions and coordinate protection, the harmonic current injected by IIDG should vary based on the severity of the fault (i.e., fault location and transition resistance). The closer the fault position to IIDG, the more severe the fault, and the greater the harmonic energy injected by IIDG. Conversely, if the fault occurs far from IIDG, the injected harmonic energy is smaller. For adjacent feeders, a relatively small harmonic energy is injected to avoid damaging normally operating loads on this feeder.[1]

Compared to setting the harmonic injection current amplitude to a constant value, this paper selects the characteristic signal amplitude as 10% of the IIDG output current RMS value, ensuring grid power quality compliance and avoiding exceeding inverter output power limits while considering the capacity of various power electronic devices. Considering that the characteristic signal is injected in the inverter current control loop and will decay after passing through the export filter and grid connection, this choice meets standard requirements.

3. Harmonic Differential Protection Strategy Based on Characteristic Signal Injection

The simplified distribution network with IIDG (Inverter Interfaced Distributed Generation) analyzed in this paper is shown in Figure 3. The IIDG is connected to the distribution network system at Bus A. Since the harmonic differential protection studied in this paper is only used to protect Load 1, harmonic differential protection devices are installed on both sides B and C to analyze the protection operation conditions.

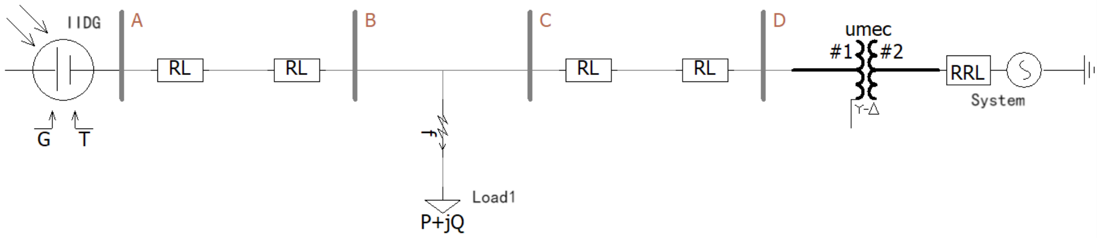


Figure 3. The structural diagram of the distribution network with IIDG integration.

3.1 Fault Occurs at the Load End

According to the fault current flow, the current flowing through fault point f is provided by IIDG. The harmonic content rate of the characteristic signal current flowing through protection n is given by:

$$HI_{n\_x} = \frac{I_{n\_x}}{I_{n\_1}} \times 100\% \tag{5}$$

where I_{n_1} is the RMS value of the fundamental current flowing through protection n; I_{n_x} is the RMS value of the x-th harmonic current flowing through protection n.

For line BC, in case of an internal fault, the harmonic content rate difference of the characteristic signal current flowing through both ends of the line is defined as ΔHI_{BC_x}. At this point, the harmonic differential protection operates, with the protection criterion being:

$$\Delta HRI_{BC\_x} = \left| HI_{B\_x} - HI_{C\_x} \right| \tag{6}$$

$$\Delta HI_{BC\_x} \geq \Delta HI_{set\_x} \tag{7}$$

where $\Delta H_n I_{set\_x}$ is the set value of the harmonic content rate difference.

3.2 Fault Occurs on Upstream Line AB

For the load, this is an external fault. Since the characteristic signal current cannot flow through protection B, the characteristic harmonic signal cannot be detected at protection B, so the harmonic differential protection devices at B and C do not operate. At this point, for line BC:

$$\Delta HI_{BC\_x} < \Delta HI_{set\_x} \tag{8}$$

3.3 Fault Occurs on Downstream Line CD

The characteristic signal current cannot flow through protection C since it is an external fault. The characteristic harmonic signal is very small, and the harmonic content rate difference is much smaller than the protection set value, so the harmonic differential protection control module does not operate. Thus, for line BC:

$$\Delta HI_{BC\_x} < \Delta HI_{set\_x} \tag{9}$$

Based on the above analysis, the protection scheme can be determined by judging the harmonic content rate difference of the characteristic harmonic signal current at both ends of the line. The protection criterion is:

$$\begin{cases} \Delta HI_{BC\_x} \geq \Delta HI_{set\_x} & \text{Internal Fault} \\ \Delta HI_{BC\_x} < \Delta HI_{set\_x} & \text{External Fault} \end{cases} \tag{10}$$

4. Multiple IIDG Characteristic Signals Simulation Verification

The simulation structure is shown in Figure 4. On the left is the PV side with irradiance of 1000 W/m^2 and temperature of 25 ℃. On the right is the system side, using Dyn connection for the transformer with rated voltages of 0.38 kV / 10 kV. The grid-connected line is 40 km long, with unit positive-sequence impedance of 0.01273+j0.9337 Ω/km and unit zero-sequence impedance of 0.3864+j4.1264 Ω/km. A load with a rated voltage of 380 V is connected at the midpoint of the line.

The system frequency is 50 Hz, and the simulation duration is 0.6 s with a sampling frequency of 5 kHz. Faults occur outside the PV side grid-connected line, inside the load end, and outside the system-side grid-connected line.

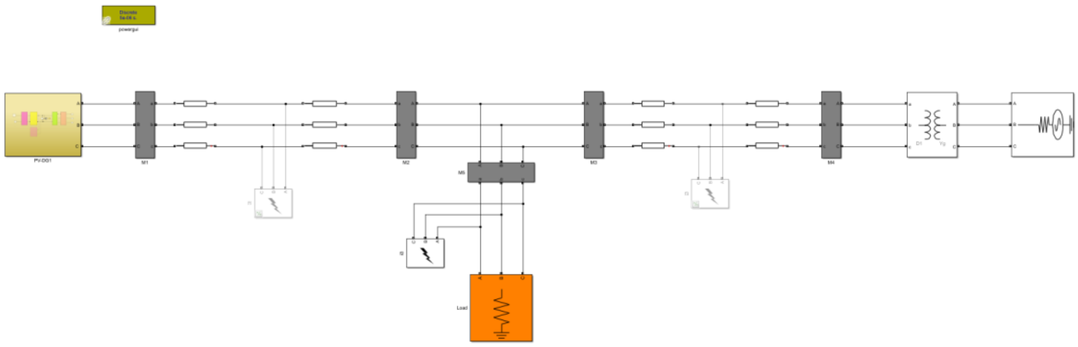
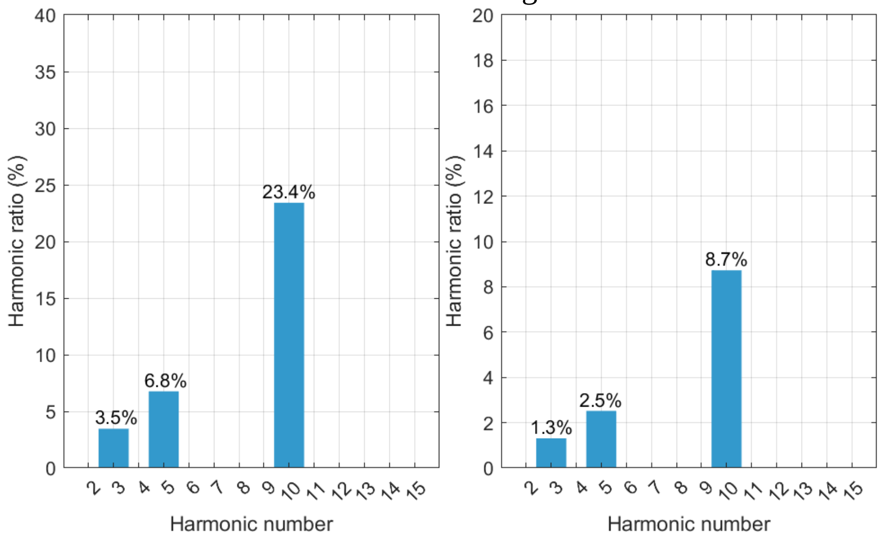


Figure 4. Simulation Structure Diagram of the Grid-Connected Photovoltaic System with IIDG.

4.1 Selection of IIDG Characteristic Signals

Inject a characteristic signal in the current control loop of IIDG in Figure 4, choosing the 10th harmonic with an amplitude of I^{inj}=0.1I^{DG} . The grid voltage level is 380 V, and IIDG is limited to 1.5 times. During normal operation of the distribution network, observe the harmonic current situation at the point of common coupling (PCC) after injecting the harmonic signal. Perform FFT calculations on the current signal, as shown in Figure 5, indicating that the injected harmonic signal strength meets the harmonic content standards for IIDG grid connection.

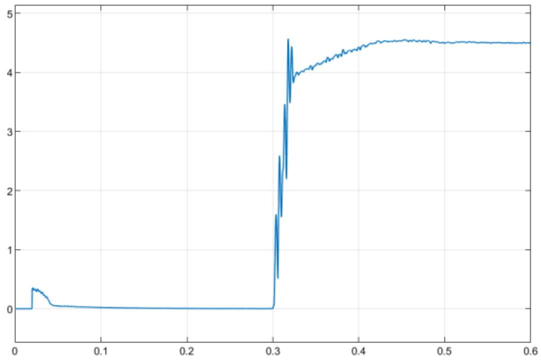


(a) Load Side (b) IIDG Connection Point

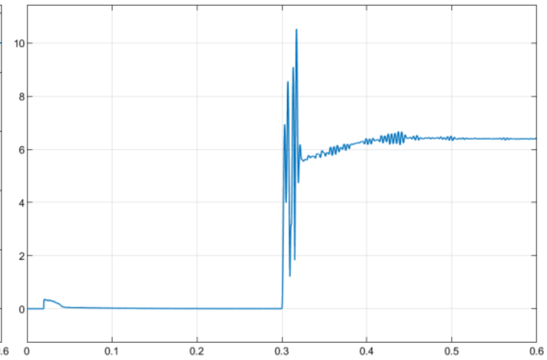
Figure 5. FFT Results of Grid Current After Characteristic Signal Injection.

4.2 Protection Verification for IIDG Characteristic Signal Injection

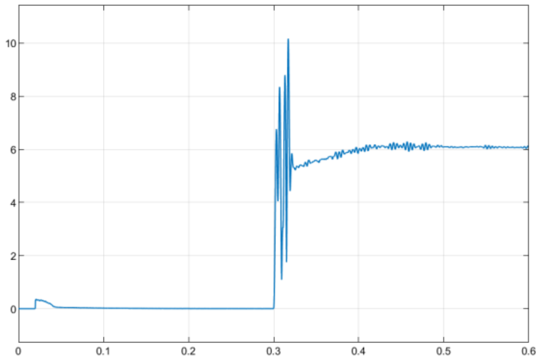
Simulate different types of faults at the load end and perform FFT analysis on the current flowing through protection M5 under fault conditions, as shown in Figure 6. After extensive simulations, the set value ΔHI_{set_x} is determined to be 3.5, meeting selectivity and sufficient sensitivity requirements.



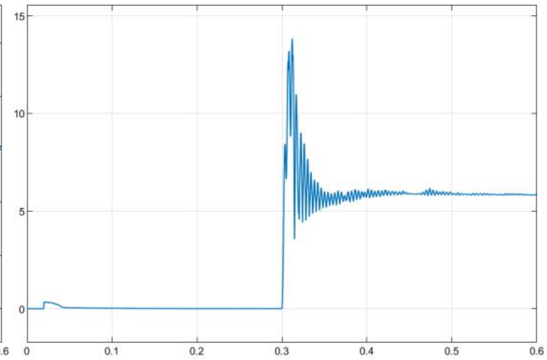
(a) A-phase Ground Fault



(b) BC-phase Two-phase Ground Fault.



(c) BC-phase Inter-phase Short Circuit



(d) Three-phase Ground Fault

Figure 6. Fluctuation Conditions of ΔHI_{BC_x} at the Load Side During Faults.

Figure 6 shows that all conditions meet the operation criteria, and the protection can successfully operate under various fault conditions. It is evident that the three-phase ground fault feature is most pronounced when the fault location is the same.

Simulations are conducted for different types of faults at fault points and fault points, performing FFT calculations on fault currents and comparing the obtained ΔHI_{BC_x} with the set value, as shown in Table 1.

Table 1 Single IIDG Characteristic Signal Injection Protection Operation Status

FAULT TYPE	**PV SIDE EXTERNAL**		**INTERNAL LOAD END**		**SYSTEM SIDE EXTERNAL**	
	ΔHI_{BC_x}	Operation Status	ΔHI_{BC_x}	Operation Status	ΔHI_{BC_x}	Operation Status
Single Phase Ground	2.8901	-	4.6832	+	2.5961	-
Two Phase Ground	2.5653	-	11.8579	+	2.2181	-
Two Phase Short	2.1960	-	10.7165	+	2.0865	-
Three Phase Ground	0.6778	-	13.7282	+	0.5675	-

From Table 1, it can be seen that the load-end harmonic differential protection can accurately operate for the above fault situations. Due to the large capacity of IIDG in the distribution network, when faults occur externally, the fault current is jointly provided by the system and IIDG, resulting in relatively higher harmonic content of the injected characteristic signal. However, based on current measurement accuracy, it can still be identified and used as a criterion.

5. Conclusion

This paper proposes a method of harmonic differential protection for PV grid-connected loads based on characteristic signal injection, aiming to solve relay protection problems caused by the integration of inverter-interfaced distributed generation (IIDG) into distribution networks. By introducing a characteristic signal injection strategy into the current inner-loop controller of inverters, the system can achieve effective fault detection and protection coordination under different fault conditions. The main conclusions are:

(1) Effectiveness of Characteristic Signal Injection Strategy : By injecting specific frequency and amplitude high-order harmonic signals into the inverter current control loop, fault features can be significantly enhanced during faults, making them easier to detect. This strategy does not affect the control loop of IIDG and is adaptable to various types of distributed power sources.

(2) Selection and Optimization of Characteristic Signals: This paper discusses the selection of characteristic signal frequency, length, and amplitude. The injected signal frequency should be lower than the filter's cutoff frequency to avoid resonance and attenuation; the signal length is set to 100 ms to ensure detection accuracy and power quality; the signal amplitude is set to 10% of the IIDG output current RMS value to ensure clear fault features without causing significant grid disturbances.

(3) Feasibility of Harmonic Differential Protection Scheme : Through theoretical analysis and simulation verification, the proposed harmonic differential protection scheme based on characteristic signal injection has been proven effective and feasible under different fault conditions.

In summary, the method of harmonic differential protection for PV grid-connected loads based on characteristic signal injection not only improves the protection performance of distribution networks but also provides new ideas and technical support for the future development of intelligent distribution networks. This method has broad application prospects and is expected to be further promoted and improved in the future.

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