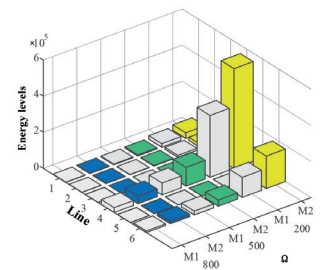


Single-phase ground fault line selection method in active distribution networks based on high-voltage inverter injected signals



Método de localización de falta a tierra monofásica en líneas de distribución en servicio basado en la inyección de señales a través de inversores acoplados en alta tensión



Zhengyi Liu^{1,2}, Changhong Deng¹

¹ School of Electrical and Automation, University of Wuhan, Bayi Road 299#, Wuhan, 430072, Hubei, China

² School of Electrical Engineering, Nanyang Technological University, 50 Nanyang Avenue, CA 639798, Singapore

DOI: <http://dx.doi.org/10.6036/9221> | Recibido: 23/04/2019 • Inicio Evaluación: 23/04/2019 • Aceptado: 14/06/2019

ABSTRACT

• Fault line selection is a major problem of distribution networks. Selection of the fault line in distribution networks is increasingly becoming difficult due to the connecting of abundant new energy resources. A fault line selection method based on injected characteristic signals by the inverter was proposed in this study to increase accuracy of fault line selection. Under fault of distribution networks, the proposed method selected fault line by changing the modulation strategy of the inverter for a short time and injecting characteristic signals. A typical simulation model of active distribution networks was constructed to analyze different earth faults in distribution networks. Accuracy of this model was verified by simulation analysis. Results demonstrate that characteristic signals at different zero-sequence current measuring points are significantly different after signals are injected. Accordingly, the fault line during faults with 500 Ω or lower ground resistance is distinguished. Under the occurrence of faults with 500 Ω or higher ground resistance, the characteristic signal injection method based on an inverter has better energy value and can increase accuracy of line selection effectively compared with the traditional energy method. This study provides certain references for fault line selection in distribution networks based on inverters.

• **Keywords:** Distribution network, Single phase ground, Signal injection, Inverter, Fault line selection.

RESUMEN

La localización de fallos a tierra en las líneas es un problema importante de las redes de distribución. La localización de la línea con fallo en las redes de distribución es cada vez más difícil debido a la incorporación de numerosos nuevos generadores de energía. En este estudio se propone un método de localización de la línea con fallo basado en señales características inyectadas por un inversor para aumentar la precisión de la localización de la línea con fallo. En el caso de las redes de distribución, el método propuesto localizó la línea fallo cambiando la consigna de modulación del inversor durante un corto periodo de tiempo e inyectando señales características. Se construyó un modelo típico de simulación de redes de distribución en servicio para analizar diferentes fallos a tierra en las redes de distribución. La precisión de este modelo

se verificó mediante análisis de simulación. Los resultados demuestran que las señales características en diferentes puntos de medición de corriente de secuencia cero son significativamente diferentes después de inyectar las señales. En consecuencia, se distingue la línea en fallo para casos con 500 Ω o menor resistencia a tierra. Si se producen fallos con una resistencia a tierra de 500 Ω o superior, el método de inyección de señal característico a través de un inversor tiene un mayor valor energético y puede aumentar la precisión de la localización de la línea de forma eficaz en comparación con el método de energía tradicional. Este estudio proporciona algunas referencias para la localización de la línea en fallo en las redes de distribución a través de inversores.

Palabras clave: Red de distribución, Puesta a tierra monofásica, Inyección de señal, Inversor, Selección de la línea de fallo.

1. INTRODUCTION

The rapid economic development proposes high requirements on reliability of electricity use. To relieve environmental damages, abundant clean energy resources have been connected into distribution networks. Distribution network has multiple branches and complicated framework, which increase difficulties in fault identification. To meet the demands of urban distribution networks, cable lines are increased continuously. The continuous connecting of electrical equipment, especially high-capacity inverters, brings great potential safety hazards to the electric system and even distribution systems. On the one hand, reliability of distribution networks is decreased, which increases the probability of fault. On the other hand, the capacitive current is increased significantly upon the occurrence of fault due to long lines and the continuously increasing proportion of cable lines. The ground arc, which is produced by ground fault, threatens safety of equipment and personnel significantly. However, the single-phase ground fault accounts for a high proportion in faults of distribution networks [1]. Connecting of new energy resources increases the output uncertainty of distribution networks, which results in great differences between fault characteristics and traditional distribution networks. Consequently, existing protective relaying in distribution networks exhibits incorrect operation and operation failure [2-3]. Thus, the single-phase ground fault is complicated in actual operation, which brings a new challenge to ground fault line selection in distribution networks.

Studies on single-phase ground fault line selection in distribution networks have been reported [4-10]. Great progresses have been achieved under low ground resistance. However, these studies pay minimal attention to influences of connecting of new energy resources on network under high impedance fault. Small size of fault data and instability of signals during single-phase ground fault bring difficulty in identifying fault lines, especially under high impedance fault. Therefore, simplification of extraction and analysis of signals under single-phase ground fault is a problem that has to be solved urgently.

On the basis of the above-mentioned analysis, a high-voltage inverter that is connected to the system directly is proposed in this study. The inverter injects characteristic signals in a short period by changing its modulation strategy under the occurrence of fault in distribution networks to conduct accurate identification of fault line.

2. STATE OF THE ART

Many studies are available on identification of single-phase ground fault in distribution networks. Line selection methods are mainly divided into identification method based on steady-state content of zero-sequence current and identification method based on transient-state content. Aziz [4] studied high impedance fault by using the amplitude and phase of the third harmonics based on the adaptive neuro fuzzy inference system (ANFIS) and three strategies for fault information extraction. However, the ANFIS has to be trained in advance. Costa [5] carried out real-time monitoring of the transient-state process of high impedance fault by using the sliding time window with variable boundaries. The study used the wavelet function and thus reduced influences of wavelet function selection on line selection. Jose [6] detected fault by using post-fault inter-harmonics. However, this fault detection method has few inter-harmonics and is time consuming. Ambikairajah [7] analyzed high impedance fault by using the wavelet coefficient and achieved good effect after using the appropriate wavelet basis function. However, this method has to select the wavelet function reasonably. Chen [8] determined the fault section through the synchronous-phase measurement units in distribution networks and the transient current and voltage phase relations. However, this method consumes a large amount of information. Li [9] analyzed transient frequency characteristics under high impedance fault and designed a filter to identify the transient characteristic frequency information. Moreover, accuracy of fault line selection was improved through hierarchical clustering method. Compared with wavelet method, this strategy avoids decomposition of multiple layers and saves computation load. However, the method can be improved further.

Wang [10] proposed a high impedance fault detection algorithm based on nonlinear resistance identification. This algorithm is constructed by extracting fault characteristics through the least square fitting. The HIF detection algorithm achieves a higher accuracy than the traditional model but fails to judge ground resistance with insignificant nonlinear characteristics. Zeng [11] proposed a frequency sweep method to measure the ground-to-ground parameters (e.g., ground capacitance and leakage resistance) before the fault. However, this frequency sweep method cannot reflect system-to-ground parameters after fault.

Santos [12] analyzed the high impedance fault by energy spectral method, which has to select the energy spectrum reasonably. The method based on artificial intelligence requires real-time updating of the judgment threshold depending on the entire net-

work state due to poor adaptation [13]. Guo [14] identified fault line by using multiple criteria. This identification method is more accurate than single method but has heavier computation loads. Wang Bin [15] introduced fault detection methods and techniques for distribution networks by using synchronous signals. Liang [16] proposed the zero-sequence characteristic ranging of lines based on post-fault distribution parameters, constructed a hyperbolic function, and identified zero-sequence parameters of fault line by using the sampling information of non-fault lines. The zero sequence current subtle makes the fault line hard to be detected.

Traditional methods for distribution network fault locating [17-18] provide insufficient consideration to connecting of distributed Generators (DGs) and its influences on characteristics of distribution network fault. Distribution networks encounter new challenges as distributed generation is connected into the system through non-isolated inverter. Connecting of considerable power electronic equipment can cause harmonic influences to power systems, which are accompanied with imbalance of zero-sequence fundamental. In normal situations, zero-sequence component produced by power electronic equipment can affect the system and may cause incorrect operation of existing line selection devices. Guo [19, 20] proposed a new modulation strategy by improving the inverter topology to decrease effects of high-frequency common mode current on power grids. This modulation strategy achieves good effect as obtained by experimentation. In the present study, energy of characteristic signals at different measuring points in distribution networks under the occurrence of fault is calculated from the injected characteristic signal of the non-isolated grid-connected inverter. The characteristic signal path is judged, and the fault line is determined. This study provides references for the characteristic signal injection method based on an inverter.

The remainder of the paper is organized as follows. Section 3 describes the distribution network model with connecting of an inverter and proposes the control process. Section 4 carries out a simulation analysis on injected signal method of the inverter and verifies the method under different faults. Section 5 presents the conclusions.

3. METHODOLOGY

A typical distribution network fault current is shown in Fig. 1 (see section: supplementary material) for an intuitive introduction of current characteristics in distribution networks. Distribution network fault line selection technologies mainly depend on detecting zero sequence current. When there is a single-phase ground fault, a fault component can be detected both in the fault line and the non fault ones. The zero-sequence component in the fault line is the sum of zero-sequence components in the perfect line. In addition, current polarity of the fault line is opposite that of the perfect line. When the arc suppression coil of the system is in the overcompensation state, the polarity of steady-state zero-sequence component cannot reflect fault line accurately.

These characteristics can also be observed in the method using transient-state component of zero-sequence current. This method has the advantage of evident transient-state component of zero-sequence current. However, the connecting of an inverter with new energy resources introduces new problems.

3.1. EFFECTS OF NON-ISOLATED CONNECTED MODE ON POWER GRID

The connecting of new energy resources increases the maximum short-circuit current capacity of the system and the fault

line becomes highly complicated. Moreover, a high-frequency component exists in the system with non-isolated connecting of a distributed power supply during modulation of an inverter. Direct injection of this high-frequency component into the power grid can affect protective relaying of the system. The direct connecting system of an inverter is shown in Fig. 2 (see section: supplementary material).

The non-isolated inverter uses PWM modulation. It often overlaps the third harmonics to increase power utilization at the DC side. A small zero-sequence component usually exists due to the system imbalance. Besides, the process of converting DC to AC in inverters will generate a little of harmonics that worsen the traditional detection systems. The permissible imbalance of normal voltage at point of common coupling of the electric system is 2% and should be lower than 4% in a short time. Direct connecting of many power electronic inverters may cause excessive imbalance of the power grid, which results in incorrect operation of protective relaying under normal circumstances.

The circuit is composed of full-controlled devices V1~V6 and parallel diodes VD1~VD6. Inductive current is supplied to V1~V6 by turns. Under the occurrence of fault, characteristic signals are modulated by the SPWM bipolar mode. The produced switching sequence is shown in Fig. 3 (see section: supplementary material).

When the amplitude of characteristic wave is higher than the amplitude of carrier signal, inductive current is supplied to the upper bridge arm of the full bridge converter. When the amplitude of characteristic wave is smaller than that of carrier signal, the inductive current of the lower bridge arm is controlled and the upper bridge arm is turned off. The difference in firing angle between different phases of bridge arm in the full bridge converter is 120°.

3.2 FAULT ANALYSIS UNDER DUAL POWER

During normal operation of system, the few zero-sequence components in the network are mainly caused by system imbalance, which meet system requirements on power quality. At the occurrence of single-phase ground fault of the system, the zero-sequence component caused by imbalance at the system side can be neglected compared with the zero-sequence component caused by single-phase earth fault. The equivalent circuit under fault conditions when the non-isolated inverter is connected into the network is shown in Fig. 4.

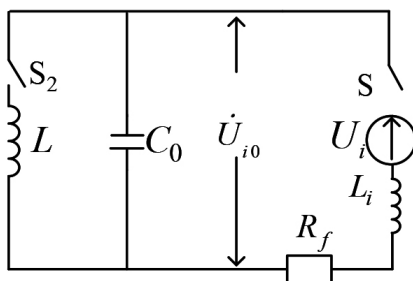


Fig. 4 Single phase ground fault equivalent circuit diagram with drive power

In Fig. 4, switch at point 1 reflects the equivalent circuit under traditional ground fault and switch at point 2 reflects injecting characteristic voltage signal through the inverter. L and C_0 represent the inductance of the arc suppression coil and the distributed capacitance of the line respectively. R_f is the ground resistance at fault points. U_{i0} and L_i are the voltage of the injected characteristic signal. The control strategy of the inverter is adjusted after the fault occurs and characteristic signals are injected into the

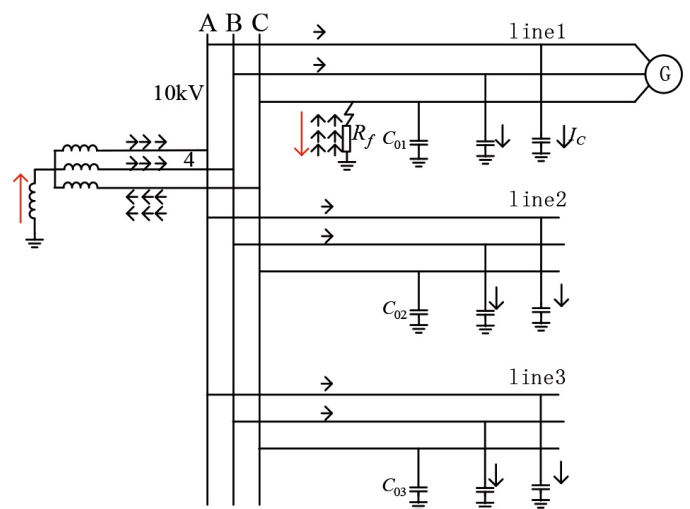


Fig. 5 Diagram of zero sequence component path

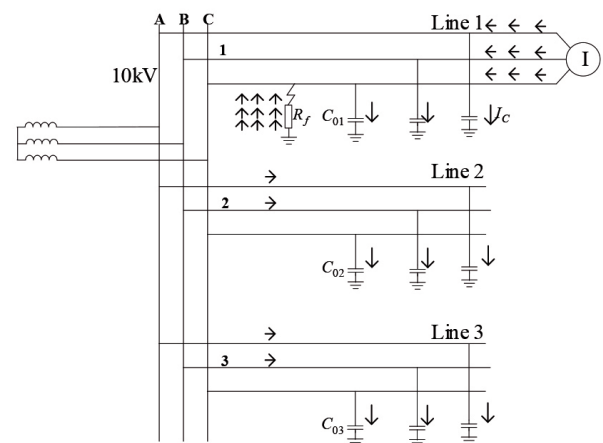


Fig. 6 Diagram of characteristic signal path

power grid through an inverter. The fault line is identified from characteristic signals on this basis.

After the occurrence of fault, the modulation strategy of the inverter is changed and voltage of the characteristic signal is injected. The position of the signal injection is the same as that of the inverters connected to the network. The produced current signal passes through the fault point and forms a loop with the distributed capacitance in the line. Given the high-frequency injected signal, the compensating current of arc suppression coil is decreased sharply in the resonant grounded system, and current distribution of characteristic signals is similar to that in the isolated neutral system. Thus, the characteristic signal path in the resonant grounded system shows no significant difference from that in the isolated neutral system. The circulation path of fundamental zero-sequence component is shown in Fig. 5, and the characteristic signal path is shown in Fig. 6.

As shown in Fig. 4, the arc suppression coil ($I_{L_{i0}}$) and distributed capacitance ($I_{C_{i0}}$) are expressed as

$$\dot{I}_{C_{i0}} = j\omega C \dot{U}_{i0} \quad (1)$$

$$\dot{I}_{L_{i0}} = \frac{1}{j\omega L} \dot{U}_{i0} \quad (2)$$

The injected characteristic signal passes through the line-to-ground capacitance, arc suppression coil inductance, and ground

resistance at fault point. The size of injected signal is m times the fundamental frequency.

Therefore,

$$\omega = m\omega_0 \quad m \in (M, M+1) \quad (3)$$

Where M is a positive integer and ω_0 is the fundamental angular frequency.

Proportions of characteristic signal in the distributed capacitance, arc suppression coil inductance, and ground resistance of the network are different under different frequencies of the injected signal. L and C are usually close to the resonant state:

$$\omega L \approx 1 / (\omega C_\Sigma) \quad (4)$$

For an injected signal, the relationship between inductive resistance in arc suppression coil and the capacitive reactance of distributed capacitance is

$$\omega L = m\omega_0 L \approx m / (\omega C_\Sigma) = m^2 / (\omega_0 C_\Sigma) \quad (5)$$

The resistance of arc suppression coil is m^2 of impedance of the distributed capacitance. The signal current is $1/m^2$ of the capacitance current. Given constant signal size, the current component at the ground point is negatively correlated with frequency of the signal. The line selection accuracy is influenced by large resistance of ground fault.

As shown Fig. 5 and 6, different distribution characteristics are observed in fundamental component of zero-sequence current and characteristic signal. Fault line can be identified according to the characteristic signal path.

3.3 INJECTION SIGNAL METHOD START-UP PROCESS

The criterion of single-phase grounding fault in distribution network is that the neutral point exceeds 15% of the phase voltage. Considering the large proportion of instantaneous grounding fault in distribution network fault, in order to avoid the influence of zero-sequence voltage on the function of the inverters caused by frequent changes in the modulation strategy of the inverters. Therefore, set a certain delay time. At the same time, it can effectively avoid the influence of fault line selection method, which is mainly based on transient signal of single-phase grounding fault current in distribution network. When the distribution network is determined to be a permanent grounding fault and there is a time delay in the transient process to avoid the fault, the control system changes the modulation strategy of the inverters. The modulation strategy of the inverters is shown in the figure. In the case of system failure, the trigger signal is sent to the reference wave for a certain time delay, and then the carrier wave is compared with the reference wave. Through the switching sequence gener-

ated by the switching device, the SPWM bipolar modulation is used to inject the characteristic current into the power grid. The switching sequence generated by the SPWM bipolar modulation is shown in Fig. 7.

3.4 LINE SELECTION METHOD BASED ON INJECTED SIGNAL

Characteristic signal is injected into the distribution network by adjusting the inverter strategy. The injected signal has to avoid the transient process of ground fault. In this study, the characteristic signal is injected by five power frequency cycles after the fault and maintained during 5 cycles. The injected signal may have corresponding transient-state processes in the power grid. Characteristic energy of the characteristic signal at different measuring points is analyzed using the time window of two power frequency cycles after the beginning of injection of one power frequency cycle.

Energy analysis can prevent problems of amplitude phase during injection of the characteristic signal. Compared with measuring amplitude phase of the characteristic signal, measuring energy of the characteristic signal can amplify the difference between the fault and perfect lines. This condition is conducive to fault identification. Therefore, comparison of energies of the characteristic signal in lines can increase the accuracy of line selection.

Energy of the single signal is equal to the sum of squares of the signal in the corresponding period. The zero-sequence voltage signal is used as the signal for identification of single-phase ground fault and the signal for changing the inverter strategy. The signal energy is expressed as Eq. (6).

$$W_i(t) = \int_{t_1}^{t_2} i_{0i}^2(\tau) d\tau \quad (6)$$

$i=1,2,3, \dots, n$, where n is the number of measuring points in the system.

$W_i(t)$ is the sum of energy at nodes of different lines in the time window. i_{0i} is the zero-sequence current in the i th line.

Signals in the characteristic time window at different measuring points of the distribution network are extracted after the characteristic signal is injected through the inverter. The energy path can be determined and the fault line can be identified through a comparative analysis on energy of the characteristic signal at different measuring points in the distribution network. This process is shown in Fig. 8 (see section: supplementary material).

Step1: The out-of-limit of zero-sequence voltage in the system is detected in the distribution network Voltage transformer (TV), and the single-phase ground fault is judged.

Step2: The inverter changes the modulation strategy and injects the characteristic signal.

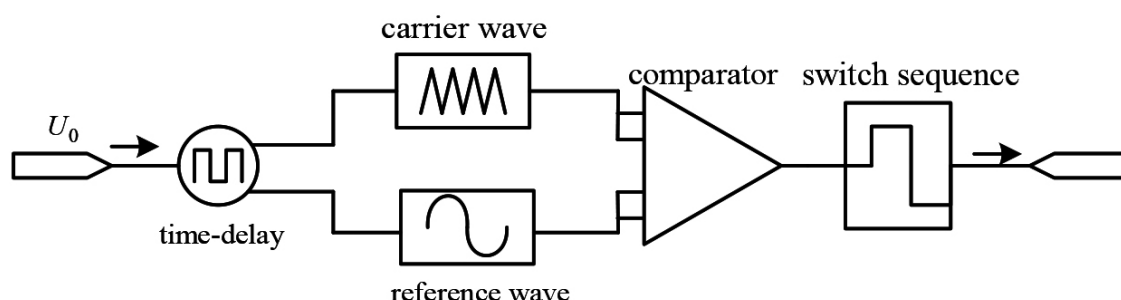


Fig. 7 Flow chart of control strategy

Phase sequence	Resistance (Ω/km)	Capacitance ($\mu\text{F}/\text{km}$)	Inductance (mH/km)
Zero sequence	0.2750	0.0054	4.6000
Positive sequence	0.1250	0.0096	1.3000

Table.1 Parameters of overhead lines

Phase sequence	Resistance (Ω/km)	Capacitance ($\mu\text{F}/\text{km}$)	Inductance (mH/km)
Zero sequence	2.7000	0.2800	1.0190
Positive sequence	0.2700	0.3390	0.2550

Table. 2 Parameters of cable lines

- Step3: Zero-sequence currents at different measuring points are obtained through the current meters at different nodes.
- Step4: Energy of the characteristic signal in the time window of two power frequency cycles after the inverter injects one power frequency cycle of current is calculated to obtain energy of the characteristic signal at different measuring points in the line.
- Step5: Energy path of the characteristic signal is determined according to its energy in a specific time window.
- Step6: The fault line is determined through the energy path.

4. RESULT ANALYSIS AND DISCUSSION

4.1 MODELING

A 10 kV typical distribution network model is constructed on the basis of three typical fault current diagrams (Fig. 9) (see section: supplementary material). When the switch is at 1, it is an arc suppression coil grounded system. When the switch is at 2, it is an isolated neutral system. "C" is the cable line and "O" is the overhead line in the fault recording indicator. The line parameters are listed in Tables 1 and 2.

4.2 SIMULATED ANALYSIS

A simulation analysis on different ground resistances is carried out under different fault positions. Energy distribution of the characteristic signal under different fault conditions is measured.

After five power frequency cycles of the fault, the inverter injects a characteristic current and detects characteristic current content at different measuring points. Energies in different lines are calculated using the above-mentioned process.

Different fault positions and types under different ground resistances are designed. For the convenience of verification, F1, F2, and F3 faults are set at the end of cable CL22 in line 2, end of line 3, and end of line 4, respectively. Each mode has its own signal energy characters. The performance of characteristic signal injection method under different ground resistances is analyzed.

4.2.1 Anti-transition resistance

Energy of different lines under 200 Ω of ground resistance at F1 fault is shown in Fig. 10(see section: supplementary material). The figure shows that energy of the characteristic signal in line 2 reaches the highest after fault happened. Therefore, the fault is determined to be at line 2. Similarly, the fault is determined at line 3 as shown in Fig. 11(see section: supplementary material). Situations under different transition resistances are analyzed, and the results are shown in Fig. 12. Fault line can be identified effectively under different resistances. However, the identification accuracy of characteristics of fault line under high resistance is decreased.

4.2.2 Fault analysis of the arc suppression coil grounded system

The neutral point is grounded through the arc suppression coil that applies the overcompensation way. The off-turning degree is 0.05. The energy distribution under F1 is shown in Fig. 13.

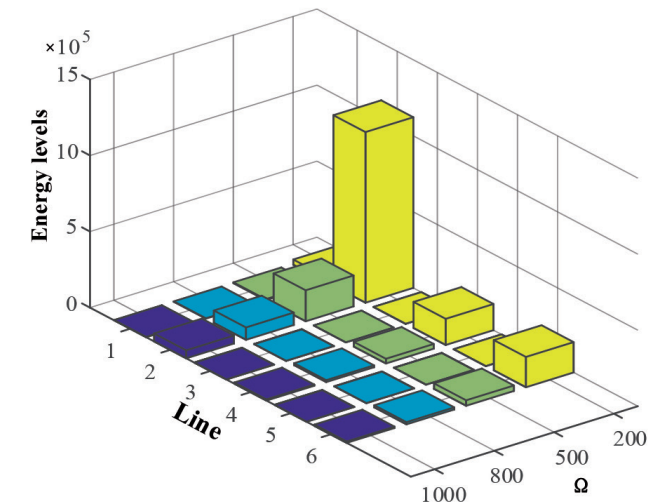


Fig. 12 Energy distribution at typical measuring points under F1

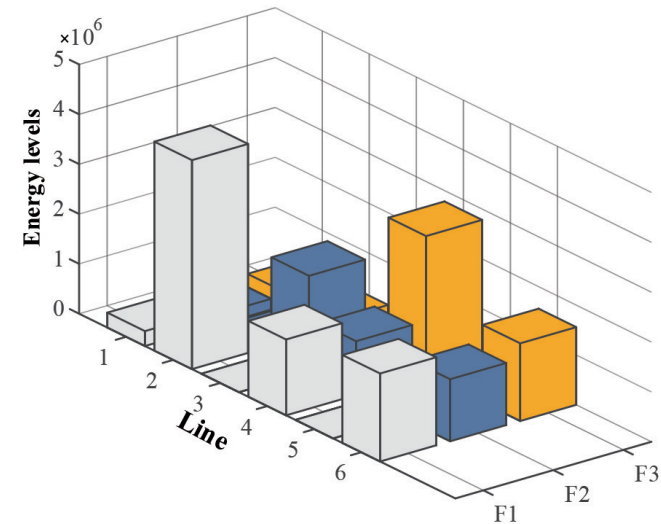


Fig. 13 Energy distribution of three fault modes under 50 Ω

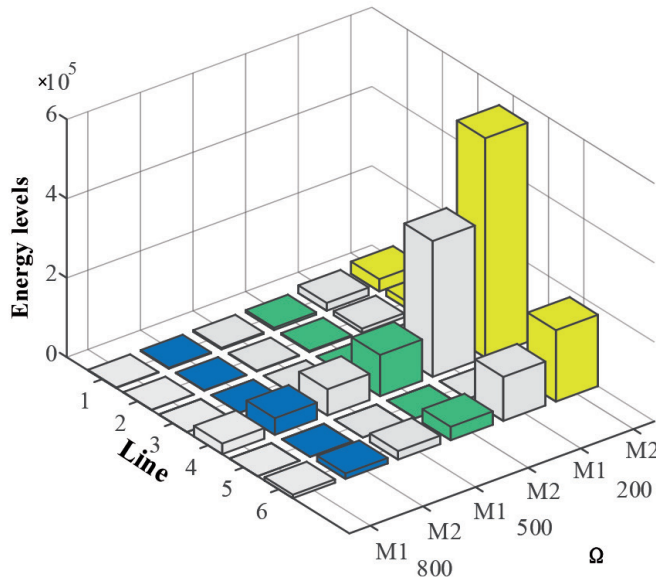


Fig. 16 Energy comparison between M1、 M2 in F3 fault

The figure shows that the characteristic signal injection method can identify fault line accurately and effectively in the arc suppression coil system. However, it still has difficulty extracting characteristic signal under high ground resistance.

4.2.3 High impedance fault

A simulation analysis on F2 and F3 is carried out on the basis of the simulation model in Section 4.1. Under low ground resistance, energy of the characteristic signal at measuring points close to the faults (F2 and F3) reaches the peak. Simulation analysis of high-resistance ground is mainly performed under 1000 Ω. As shown in Figs. 14 and 15(see section: supplementary material), energy of the characteristic signal of fault line is the highest. The energy level is relatively lower than that under low ground resistance. This result is mainly attributed to the amplitude performance of the characteristic signal in fault line under high ground resistance. By contrast, the characteristic signal current component of the ground capacitance in a perfect line of the distribution network is increased. However, fault line can still be identified under high impedance fault.

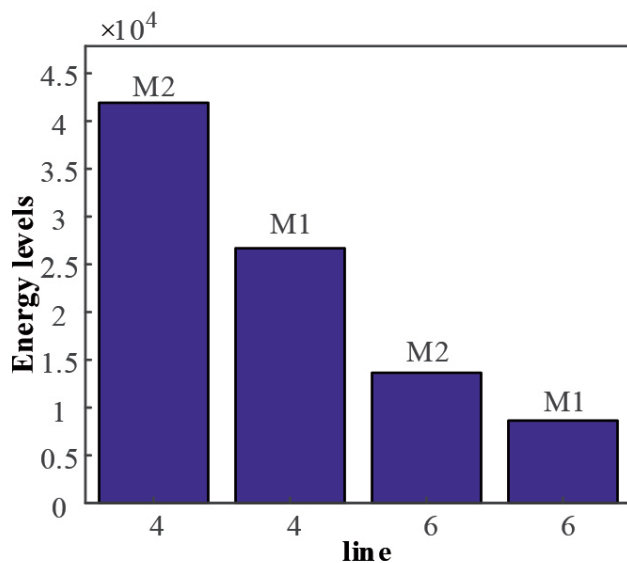


Fig. 17 Energy level of node 4 and 6 in Two Methods

4.3 COMPARISON WITH THE TRADITIONAL ENERGY METHOD

The traditional energy method compares energy of lines under fault conditions. The line with the highest energy is identified as the fault line. On the basis of the simulation model in Section 4.1, energy of the characteristic signal under 1000 Ω of F3 is calculated. The energy distribution obtained from the traditional energy method is M1, and the energy distribution obtained from the signal injection method is M2. Difference in energy obtained by the two methods is compared (Fig. 16). The sampling time is set the same as above-mentioned.

Energies obtained by M1 and M2 are compared, and the results are shown in Fig. 16. The energy difference in M1 is smaller than that in M2. Therefore, the characteristic signal injection method is beneficial for identification of fault line.

E_{iM1} and E_{iM2} are defined as energy levels of each line. Define E_i % as energy lifting degree. The larger the energy lifting degree, the easier to detect the characterization energy. D_{ijM1} and D_{ijM2} are defined as the energy level difference between line i and line j . Definition of ΔD_{ij} % is the fault identification degree. The greater the fault identification degree, the easier the correctness of fault line selection.

$$\Delta E_i \% = (E_{iM2} - E_{iM1}) / E_{iM1} \quad (7)$$

$$D_{ijM1} = E_{iM1} - E_{jM1} \quad (8)$$

$$D_{ijM2} = E_{iM2} - E_{jM2} \quad (9)$$

$$\Delta D_{ij} \% = (D_{ijM2} - D_{ijM1}) / D_{ijM1} \quad (10)$$

In the case of 800Ω grounding resistance in F3 fault mode as an example, the points with the largest energy and the points with the second largest energy are selected, and the data are shown in the Fig. 17.

Under F3 fault mode and 800Ω grounding resistance, the results of M1 and M2 methods indicate that: E_4 % is 57.1% and E_6 % is 57.1%. ΔD_{ij} is 56.7%. Thus, the lifting degree of M2 is 157.1% of M1 method. Fault identification degree increased by 56.7%.

5. CONCLUSION

A novel method based on high-voltage inverter injected signals was developed for connecting power electronics into distribution networks to increase accuracy of fault line identification. Under the occurrence of fault, the inverter injected a characteristic signal into the network in a short period. Fault current in an appropriate time window was analyzed. The following conclusions could be drawn:

(1) The characteristic signal path can reflect the section of fault location effectively under ground fault. The characteristic energy signal is evident.

(2) Under high impedance fault of the system, the characteristic signal has to pass through the transition resistance. Energy of the characteristic signal in the fault line also decreases to some extent. However, fault can still be identified accurately.

(3) The proposed fault line selection method based on injected signal has a larger fault ranging and stronger anti-transition resis-

tance under high resistances than the traditional energy method.

In this study, a fault line selection method based on injected signal of the inverter is proposed. This method conforms to future requirements of network development on functional diversity. This study provides certain references to works on inverter injection signal. Considering lack of practical data for comparison, future studies should focus on increasing the accuracy of signal injection method.

REFERENCES

- [1] Girgis A A, Chang W, Makram E B. "Analysis of high-impedance fault generated signals using a Kalman filtering approach". IEEE Transactions on Power Delivery. October 1990. Vol. 5-4: p.1714-1724. DOI: <http://dx.doi.org/10.1109/61.103666>
- [2] Firouz Y, Farhakhani S, Lobry J, et al. "Numerical comparison of the effects of different types of distributed generation units on overcurrent protection systems in MV distribution grids". Renewable Energy. September 2014. Vol. 69. p.271-283. DOI: <https://doi.org/10.1016/j.renene.2014.03.035>
- [3] Conti S, Nicotra S. "Procedures for fault location and isolation to solve protection selectivity problems in MV distribution networks with dispersed generation". Electric Power Systems Research. January 2009. Vol. 79-1. p.57-64. DOI: <https://dx.doi.org/10.1016/j.epsr.2008.05.003>
- [4] Aziz M S A, Hassan M A M, Zahab E A. "High-impedance Faults Analysis in Distribution Networks Using an Adaptive Neuro Fuzzy Inference System". Electric Power Components and Systems. August 2012. Vol. 40-11. p.1300-1318. DOI: <https://doi.org/10.1080/15325008.2012.689418>
- [5] Costa F B, Souza B, Brito N, et al. "Real-Time Detection of Transients Induced by High Impedance Faults Based on the Boundary Wavelet Transform". IEEE Transactions on Industry Applications. November 2015. Vol. 51-6. p.1-1. DOI: <https://dx.doi.org/10.1109/TIA.2015.2434993>
- [6] José Rubens Macedo, José Wilson Resende, Jr C A B, et al. "Proposition of an interharmonic-based methodology for high-impedance fault detection in distribution systems". IET Generation Transmission & Distribution. August 2015. 9-16. p.2593-2601. DOI: <https://dx.doi.org/10.1049/iet-gtd.2015.0407>
- [7] Ambikairajah E, Zhang D, Phung T, et al. "Detection of high impedance faults using current transformers for sensing and identification based on features extracted using wavelet transform". IET Generation, Transmission & Distribution. June 2016. Vol.10-12. p.2990-2998. DOI: <https://dx.doi.org/10.1049/iet-gtd.2016.0021>
- [8] CHEN Xiaoru, XUE Yongduan, WANG Chao, et al. "Synchronous Measurement Based Transient High Resistance Earth Fault Location in Resonant Grounding System". Automation of Electric Power Systems. November 2016. Vol. 40-22. p.93-99,146. DOI: <https://dx.doi.org/10.7500/AEPS20160315016>
- [9] LI Y, Meng X, Song X, et al. "Single-Phase-To-Ground Fault Line Detection for Distribution Network Based on Optimal Finite Impulse Response Filter and Hierarchical Clustering". Power System Technology. January 2015. Vol. 39-1 p.143-149. DOI: <https://dx.doi.org/10.13335/j.1000-3673.pst.2015.01.022>
- [10] Bin W, Jianzhao G, Xinzhou D. "Analysis and Detection of Volt-ampere Characteristics for High Impedance Faults in Distribution Systems". Proceedings of the Csee. August 2014. Vol.34-22. p.3815-3823. DOI: <https://dx.doi.org/10.13334/j.0258-8013.pcsee.2014.22.029>
- [11] Zeng X, Xu Y, Wang Y. "Some Novel Techniques for Insulation Parameters Measurement and Petersen-Coil Control in Distribution Systems". IEEE Transactions on Industrial Electronics. May 2010. Vol. 57-4 p.1445-1451. DOI: <https://dx.doi.org/10.1109/TIE.2009.2029513>
- [12] Santos W C, Lopes F V, Brito N S D, et al. "High-Impedance Fault Identification on Distribution Networks". IEEE Transactions on Power Delivery. January 2017. Vol. 32-1. p.23-32. DOI: <https://dx.doi.org/10.1109/TPWRD.2016.2548942>
- [13] Rafinia A, Moshtagh J. "A new approach to fault location in three-phase underground distribution system using combination of wavelet analysis with ANN and FLS". International Journal of Electrical Power & Energy Systems. February 2014. Vol. 55. p.261-274. DOI: <https://dx.doi.org/10.1016/j.ijepes.2013.09.011>
- [14] Guo M, Yan M, Chen B, et al. "Faulty line selection based on waveform feature clustering in time domain for resonance grounding system". Electric Power Automation Equipment. November 2015. Vol.35-11. p.59-66,81. DOI: <https://dx.doi.org/10.16081/j.issn.1006-6047.2015.11.010>
- [15] Wang B, Sun H, Zhang D. "Review on data sharing and synchronized phasor measurement technique with application in distribution systems". Proceedings of the Csee. September 2015. Vol.35(s). p.1-7. DOI: <https://dx.doi.org/10.13334/j.0258-8013.pcsee.2015.5.001>
- [16] Liang R, Yang X, XUE X, et al. "Study of Accurate Single-phase Grounding Fault Location Based on Distributed Parameter Theory Using Data of Zero Sequence Components". Transactions of China Electrotechnical Society. June 2015. Vol. 30-12. p.472-479. DOI: <https://dx.doi.org/10.3969/j.issn.1000-6753.2015.12.060>
- [17] André D. Filomena, Resener M, Salim R H, et al. "Fault location for underground distribution feeders: An extended impedance-based formulation with capacitive current compensation". International Journal of Electrical Power & Energy Systems. October 2009. Vol.31-9. p.489-496. DOI: <https://dx.doi.org/10.1016/j.ijepes.2009.03.026>
- [18] Wang P, Tian C, Chen B, et al. "Electromagnetic hybrid arc suppression and a novel method of feeder selection based on the novel magnetic controlled petersen coil". Transactions of China Electrotechnical Society. August 2015. Vol.30-16. p.175-183. DOI: <https://dx.doi.org/10.3969/j.issn.1000-6753.2015.16.023>
- [19] Guo X. "Three-Phase CH7 Inverter With a New Space Vector Modulation to Reduce Leakage Current for Transformer less Photovoltaic Systems". IEEE Journal of Emerging & Selected Topics in Power Electronics. January 2017. Vol.5-2. p.708-712. DOI: <https://dx.doi.org/10.1109/JESTPE.2017.2662015>
- [20] Guo X, Wei B, Zhu T, et al. "Leakage Current Suppression of Three Phase Flying Capacitor PV Inverter with New Carrier Modulation and Logic Function". IEEE Transactions on Power Electronics. March 2018. Vol. 33-3, p. 2127-2135. DOI: <https://dx.doi.org/10.1109/TPEL.2017.2692753>

SUPPLEMENTARY MATERIAL

https://www.revistadyna.com/documentos/pdfs/_adic/9221-1.pdf

