Relay protection of multilevel differential distribution network based on feeder segment switch

Qingjie Wang

School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 071003, China

E-mail: jing365788594@163.com

Abstract: In order to solve the problems existing in the traditional relay protection methods, such as poor relay safety and large fault location error of distribution network, this paper proposes a multilevel differential relay protection method based on feeder segment switch. The configuration principle and the selection principle of multilevel range are determined, and the objective function of multilevel difference distribution network feeder segment switch configuration is set. After considering the target of economic benefit, the main feeder of distribution network is segmented and a contact switch is set at the end of the feeder. The equivalent topology of multilevel differential distribution network is analyzed to make the power supply at the first end of the line connected with the substation, which is regarded as the ideal voltage source. Considering the jurisdiction index of the switch, greedy algorithm is adopted to optimize the switch configuration of feeder segment. This paper analyzes the protection misoperation of multilevel differential distribution network and the sensitivity of feeder segment switch to realize the relay protection of multilevel differential distribution network. The experimental results show that the proposed method has higher safety and lower fault location accuracy, and is feasible to some extent.

Key words: Feeder Segment Switch; Multistage differential; Relay protection; Objective function; Greedy algorithm; Protection of maloperation; Sensitivity

1 Introduction

With the industrial development and economic growth, the modern power system characterized by "large units, large capacity, high voltage, long distance, new technology and intelligence" is constantly improving in operating efficiency, but at the same time, operating complexity and uncertainty are also increasing (Boyer et al. 2018). System operation features as the grid size, the change of regional distribution of power grid, power grid structure, diversity, and present a more complex due to the electrical connection and integrity, the same power network in a variety of possible running state and fault state there are both differences and similarities of characterization: electric power market gradually developed, and the safe operation of power system has brought certain influence, maximum limit to carry out the market may lead to safety margin narrowed to the limit; Many market participants play an increasingly important role, which adds changeable and uncertain factors to power grid operation (Twyford et al. 2020). In recent years, the access of large-scale new energy power further aggravates the influence of random factors on the power system. As the first line of defense to ensure the safety of the power grid, the reliable operation of the relay protection system is of great significance to the safety and stability of the power system, but its rejection and misoperation are also one of the important factors that trigger or accelerate the system disturbance (Rajput et al. 2018). Therefore, researchers in this field have done a lot of research on it.

Esteve-Llorens et al. (2020) proposes a power grid fault diagnosis method that takes into account the reliability assessment of relay protection devices. With the help of the non-strongly related alarm information, the markov model of relay protection is constructed, and the probability of protection misoperation and misoperation is solved by the state space method. Will get the results into the power grid fault diagnosis method based on the analytical model of the objective function, and the use of variable length chromosome genetic algorithm the optimal fault hypothesis, complete the evaluation of the reliability of relay protection device and power grid fault diagnosis, this method can effectively evaluate the reliability of relay protection device, and through the analysis of the cause of the power grid failure, has certain reliability, but the method of relay protection device in the corresponding less influence factors analysis, were some safety problems. Ren et al. (2019) proposed the research on the online checking sequence of relay protection fixed value based on the combination weight method of relative entropy. This method constructs a comprehensive protection importance evaluation model from two perspectives, namely, the critical degree of the network location where the comprehensive protection is located and the severity of the consequences of the protection failure. Based on the active power flow medium of the branch, the importance index of the branch is proposed to quantitatively evaluate the key degree of the branch where the protection is located. The severity index of protection fault is put forward by combining protection fault chain model with risk theory to quantitatively evaluate the risk consequence of protection fault chain. A protection fit index is proposed to quantitatively evaluate the topology vulnerability of the protection location. In order to make up for the limitation of single weighting method, the relative entropy combined weighting method is used to calculate the weight of each index, and then the index of comprehensive importance degree of protection is obtained (Li et al. 2020; Duarte et al. 2019). The comprehensive importance index of relay protection obtained by this method has a high precision and can effectively analyze the setting value of relay protection to protect the safe operation of power system. However, in the process of obtaining the fixed value of relay protection, this method has the problem of weak anti-interference and some limitations. Wang et al. (2018) presents a new online monitoring method for relay protection based on the characteristics of smart substation system. The online monitoring function demand of relay protection is analyzed comprehensively and the online monitoring idea of relay protection is put forward. The intelligent substation fault information model including primary system interval model, secondary system port model and secondary system logic model is established. On this basis, the coupling and correlation between relay protection state information is fully described, and the key state of relay protection is automatically identified, and the fault location of relay protection is realized. The results of example analysis show that based on the fault information model of smart substation, the online monitoring method of relay protection can realize the identification of key states of relay protection. This method can effectively improve the safety performance of relay protection, but it has a low accuracy in locating power grid faults.

Based on the shortcomings of the above methods, this paper proposes a multilevel differential distribution network relay protection method based on feeder segment switch. The method determines the configuration principle and the selection principle of multilevel range, and sets the objective function of multilevel difference distribution network feeder segment switch configuration. After considering the target of economic benefit, the main feeder of distribution network is segmented and a contact switch is set at the end of the feeder. (Rajalakshmi and Durairaj 2020; Li et al. 2019) The equivalent topology of multilevel differential distribution network is analyzed to make the power supply at the first end of the line connected with the substation, which is regarded as the ideal voltage source. Considering the jurisdiction index of the switch, greedy algorithm is adopted to optimize the switch configuration of feeder segment.

This paper analyzes the protection misoperation of multilevel differential distribution network and the sensitivity of feeder segment switch to realize the relay protection of multilevel differential distribution network. The technical route studied in this paper is as follows:

(1) Determine the configuration principle of the segmenting switch of feeder in distribution

network and the selection principle of multi-stage range, and set the objective function of the configuration of the segmenting switch of feeder in distribution network with multi-stage difference;

(2) After considering the objective of economic benefits, the main feeder of the distribution network shall be segmented and a contact switch shall be set at the end of the feeder; The equivalent topology of multilevel differential distribution network is analyzed to make the power supply at the first end of the line connected with the substation, which is regarded as the ideal voltage source. Considering the jurisdiction index of the switch, greedy algorithm is adopted to optimize the switch configuration of feeder segment.

(3) Analyze the protection misoperation of multilevel differential distribution network and the sensitivity of feeder segment switch to realize the relay protection of multilevel differential distribution network

(4) Experimental analysis.

(5) Conclusions and future prospects.

2 Distribution network feeder segment switch configuration and optimization

2.1 Distribution network feeder segment switch configuration

In order to realize the multi-level difference distribution network relay protection method, firstly determine the multi-level difference of distribution network relay protection, and start with the principle of its configuration to realize the two-level difference protection of distribution network. The following principles should be followed when choosing the circuit switch and protection of distribution network:

(1) Main feeder switches of distribution network generally choose load switches to meet the requirements of relay protection.

(2) In the selection of feeder switches in distribution network, user switches and branch switches have high requirements. In this paper, feeder switches are segmded and circuit breakers are adopted to set their protection delay to 0 s;

(3) The requirement of outgoing switch in substation is also very important, so the circuit breaker is selected and its protection delay is set to 200ms ~250ms (Dimitrios et al. 2018).

The following principles should be followed when selecting multilevel difference:

(1) In case of fault of distribution network branches or users, the corresponding sectional feeder switch will trip immediately and the fault will be removed. When the substation outlet feeder switch does not trip, it will not lead to a full-line power outage;

(2) During the normal operation of the power network, the phenomenon of multi-stage tripping or step-over tripping of the feeder switch should be avoided. At this time, the feeder switch should be segmented and fault determination method should be adopted.

(3) Main lines of distribution network adopt load switch to reduce project cost.

On the basis of the above principles, feeder section switch is set up to realize relay protection of distribution network. Generally speaking, the optimal switch allocation of distribution network generally starts from the two aspects of power system reliability and economy, but according to the actual situation, investors may have some differences in the objective of the optimal switch allocation of distribution network.

On the premise that the system meets a certain reliability index, the investment cost of switching equipment and its operation and maintenance cost are taken as the minimum target. In this case, the objective function of distribution network switch configuration can be expressed as:

$$P_1 = \min(A_s + A_m) \tag{1}$$

In the formula , A_s represents the investment cost of feeder switches in distribution networks , A_m represents the operating and maintenance costs of feeder switches.

In order to achieve the optimal economic benefits of the distribution network, the sum of the investment cost, operation and maintenance cost of the switching equipment and the user's loss of power is the lowest. In this case, the objective function of the distribution network switch configuration can be expressed as:

$$P_2 = A_s + A_m + oc \tag{2}$$

In the formula, oc is the user power loss cost.

After considering the objective of economic benefits, the feeder switch of distribution network is segmented (Zhang et al. 2020). Normally, switches in the distribution network are designed with a closed-loop structure, but their operation mode is open-loop operation. Therefore, this paper segmented the main feeders of the distribution network, and set a contact switch at the end of the feeders, as shown in Figure 1:

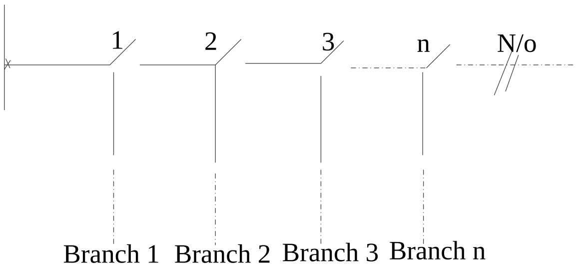

Fig. 1 Main feeder segment of distribution network

2.2 Optimization of Feeder Segmented Switch Based on Greedy Algorithm

After the feeder segment of distribution network, the segmented switch is designed. The equivalent topology diagram of multilevel differential distribution network is shown in Figure 2.

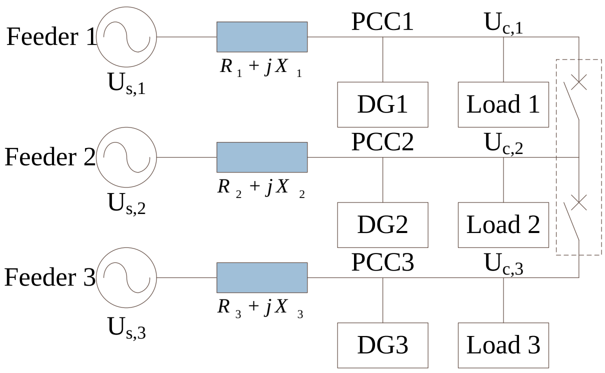

Fig. 2 Equivalent topology of multistage differential distribution network

As can be seen from Figure 2, in the multilevel differential distribution network, different feeders are connected by the contact switch. For feeders, the power supply at the front end of the line is connected to the substation and can be regarded as an ideal voltage source.

In order to improve the relay protection of multistage distribution network, it is assumed that the first terminal voltage of one feeder is U_s ,Voltage is U_c on the PPC ,the active and reactive currents flowing through the feeder are I_d and I_q ,The voltage relationship between the power end and PPC is shown in Figure 3:

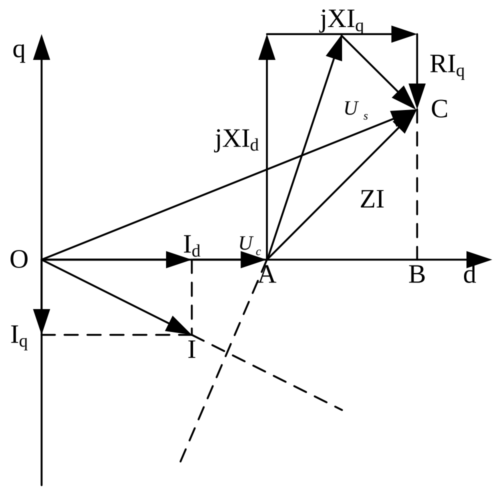

Fig. 3 The voltage vector diagram of the power end and *PPC*

In the above analysis, in the design of feeder segment switches, the jurisdiction index of switches should be considered, which can protect the maximum short-circuit current at the end and the minimum trip current at the regional head switch (Stepanov et al. 2019). That is:

$$\varphi_k = \frac{W_{\max k}}{W_{\min k}} = \frac{W_{\max k}}{2W_{\max k}} \tag{3}$$

In the formula, $W_{\max k}$ represents the maximum short circuit current at the end of the protected area , $W_{\min k}$ represents the minimum tripping current at the first end of the area switch, $2W_{\max k}$ represents the maximum load current at the first end of the area switch.

When the minimum tripping current is the same , φ_k is greater the value, and the higher its switching sensitivity (Karunananthan et al. 2019). The more segment switches are needed, the greater the investment. As a result, in the determination of the number of feeder segment switches, it is necessary to set up with the secondary feeder and the main feeder node, that is, the ., from the close side of the power supply $\{1, 2, ...n\}$ .On this basis, the power flow and short circuit of the distribution network are calculated to obtain the. When the substation is out of line, circuit breakers are generally installed , let $k = 1$ 、 $n = 0$,if the node and the neighbor node are set up, the feeder segment switch is obtained, and the feeder segment switch is set.

he basis of the above segmented feeder switches Settings, the number of segmented feeder switches is not changed, and their positions are optimized to find the optimal position of segmented switches, so that the performance of distribution network can reach the best. At this time, the reliability index of segmented feeder switches in distribution network is selected as the average supply availability index ASAIP (Sharma et al. 2018; Li et al. 2021). Therefore, the objective function of feeder segment switch is:

$$P = \max ASAI \tag{4}$$

When setting feeder segment switch, the average power supply availability index ASAI is the same, so it needs to consider the way of setting with small power loss of distribution network users. Due to the limitation of the algorithm itself, the greedy algorithm should ensure that the segmented switches on the main feeder lines of the distribution network are optimized, and the number of optimized switches will not change. The improved mathematical model is as follows:

$$\min A = A_s + A_m$$
$$s.t \quad \varepsilon_i \geq \sum_{i=1} \lambda_i \tag{5}$$

In the formula, ε_i representing the load capacity i distribution network nodes , λ_i represents the load value of the load point.

3Relay Protection Method for Multistage Differential Distribution Network

After the optimization of the feeder section switch, the relay protection method is designed for multilevel differential distribution network. In safe operation of the distribution network, the current protection of wiring can generally reliable and rapid removal of obstacles, but due to the influence of the electric power system, power distribution network access when the power is distributed, the grid node trend change, in components run, the size and direction of short circuit current are likely (Zhou et al. 2020) great changes have taken place. Since the multilevel difference of the distribution network changes after the distributed power supply is connected, the size and operation direction of short-circuit current of the distribution network may change, so it is necessary to relay the protection. When the fault occurs in the multilevel differential distribution network, relay protection device is used to protect the fault. Among them, the protection misoperation in the distribution network needs to be dealt with. Protection misoperation generally occurs in distribution network wiring, as shown in Figure 4:

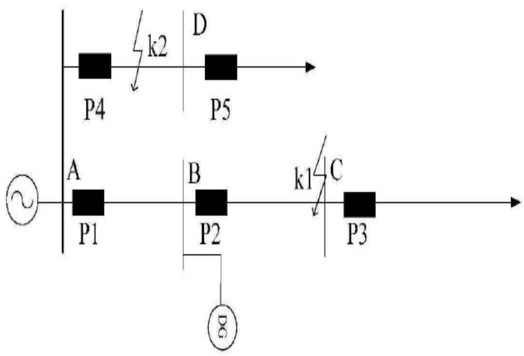

Fig. 4 Distribution network diagram

When a short circuit fault occurs KI the end of the line BC or the outlet side of the lower line, the protection current P2 can be obtained. The larger the capacity and the greater the current of the distributed power supply, which may be larger than the setting value of the P2 protection, resulting in the protection misoperation (Freitas et al. 2018).

Assumption Z_a represents the equivalent impedance of a power system, Z_1、Z_2 is the impedance values of multistage differential distribution network lines, Z_b represents the equivalent impedance of distributed power, R_{z_b} represents the capacity of distributed power supply, the protection misoperation of multistage differential distribution network can be solved by formula (6), that is:

$$I_{P2} = \frac{1}{\frac{(Z_a + Z_1)Z_b}{Z_a + Z_1 + Z_b}} \times R_{Z_b} \tag{6}$$

On the basis of the above analysis, the protection misoperation of multistage differential distribution network is also affected by the sub-transient reactance of distributed power supply.

Assumption $C_b = 100MVA$, $D_v = 10.5kV$,and F_{dg} represents the sub-transient reactance of a distributed power supply, there are:

$$Z_{dg} = \frac{F_{dg} \times 100}{C_b \times D_v} \tag{7}$$

As the C_b、 D_v grows, With the continuous increase, I_{P2} can be effectively suppressed to realize the treatment of misoperation of multilevel differential distribution network protection.

The load power supply capacity of the power grid in different regions can be reflected by the capacity-load ratio. At fixed time, the ratio between the total substation capacity of different regions of the smart grid and the corresponding load to be evaluated is the capacity-load ratio of this region of the smart grid (Barker et al. 2019), and its formula is as follows:

$$R = \frac{\sum Z_i}{P_{\max}} \tag{8}$$

In the formula, $P_{\max}$ and $\sum Z_i$ represents the maximum load of the maximum load day at different voltage levels and the total capacity of the substation put into operation on the annual maximum load day, R represents the load ratio.

There are K2 faults in the line AD in Fig .3, and the short circuit that occurs when the P1 will flow through the distributed power supply is protected. At this time, with the help of the feeder segment switch to cut off, the protection of multi-stage differential distribution network flow through the P1 of the short-circuit current is:

$$I_{P1} = \frac{1}{\frac{(Z_a + Z_1)Z_{dg}}{Z_a + Z_1 + Z_{dg}} + \psi Z_4} \times \frac{Z_a}{Z_a + Z_1 + Z_{dg}} \tag{9}$$

Synthesizing the above analysis, in solving the protection misoperation fault of multistage differential distribution network, it is necessary to block the protection misoperation change of different nodes in distribution network with the help of feeder segment switch.

Based on the analysis of protection maloperation of multistage differential distribution network, the sensitivity of feeder segment switch in the face of fault should be analyzed. On the BC line, when a short circuit fault occurs at the K1 point, the short circuit current provided by the power grid system side decreases due to the access of the distributed power supply. If the sensitivity of feeder segment switch is reduced, it will lead to distribution network failure and difficult to ensure the normal operation of the system. First, the short circuit current flowing through the protection P1 is analyzed as follows:

$$I_{P1} = \frac{1}{\frac{(Z_a + Z_1)Z_{dg}}{Z_a + Z_1 + Z_{dg}} + \psi Z_4} \times \frac{Z_a}{Z_a + Z_1 + Z_{dg}} \times I_B \tag{10}$$

In this case, the larger the value of ψ is, the smaller the value of $IP1$ is the farther the fault point of the multilevel differential distribution network is from the power side of the system, and the smaller the short circuit current of the system is. At this point, the feeder segment switch can sensitively detect the existence of faults and timely open the protection device to avoid the occurrence of faults.

The influencing factors of multilevel differential distribution network faults also need to be explored. Bayesian network, association analysis, cluster analysis and other methods can be used to clarify the probabilistic causal relationship between different indicators and their influencingfactors, and the sensitivity analysis method of feeder segmental switching can also be used to establish the optimal power flow model (Yap et al. 2018), namely:

$$\begin{cases} P_i = P_1 + \kappa_d \sum_i y_{1i} P_{1i} \\ P_j = P_2 + \beta\kappa_d \sum_i y_{2i} P_{2i} \\ ..... \\ P_{ni} = P_n + \beta\kappa_d \sum_i y_n P_{ni} \end{cases} \tag{11}$$

In the formula, P represents distribution network nodes, κ_d represents the distribution network strategic indicators, β represents the parameter variable representing the influence index of distribution network.

Based on the above analysis, the relay protection of multilevel differential distribution network is mainly realized by analyzing the protection misoperation of the power network and the sensitivity reflected by the feeder segment switch.

4 Experimental analysis

4.1 Experimental environment

In order to verify the scientific effectiveness of the proposed method, experimental analysis was carried out. A typical multilevel differential distribution network system is used in the experiment. The experiment is carried out on the MATLAB platform. The experimental operating system is a WINDOWS XP system. The experimental position of the feeder segment switchgear in the multilevel differential distribution network is shown in Figure 5:

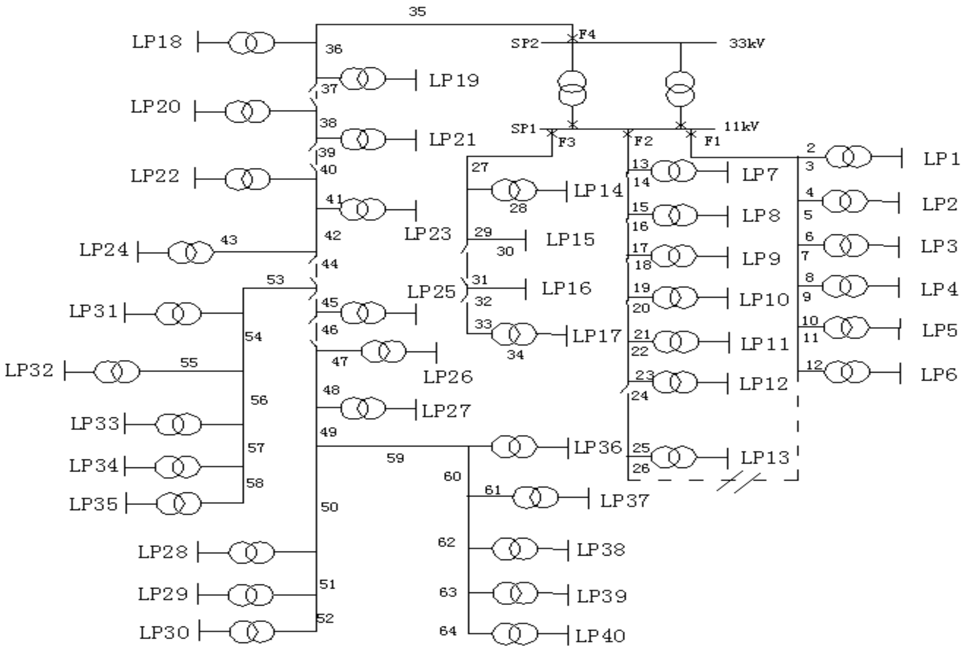

Fig. 5 Multistage differential feeder segment switch settings

4.2 Experimental parameters

The experimental parameters are shown in Table 1:

Table 1 Experimental parameters

Type of feeder	Line length/ km	Line segment
1	0.6	2/6/10/14/17/21/2528/30/34/41/47
2	0.75	1/4/7/9/12/16/19/22/24/27/29/32/61
3	0.8	3/5/8/11/13/15/18/20/23/26/31/33/47

4	0.94	38/44
5	1.8	37/39/42/49/54/62
6	2.4	36/40/52/57/60
7	2.6	35/46/50/56/59/64
8	3.7	45/51/53/58/63
9	3.9	48

Under the above experimental environment and experimental parameter design, the proposed method, literature (Esteve-Llorens et al. 2020) method and literature (Ren et al. 2019) method are used to verify the scientific effectiveness of the proposed method, respectively, from the point of view of relay protection safety and fault location accuracy of distribution network.

4.3 Analysis of experimental results

4.3.1 Safety Analysis of Relay Protection in Different Methods

To verify the scientific effectiveness of the proposed method, the relay protection safety of the proposed method, the literature (Esteve-Llorens et al. 2020) method and the literature (Ren et al. 2019) method is analyzed experimentally. The safety factor is mainly reflected by the safety factor. The value of the safety factor is [0,1]. The higher the value, the higher the safety. The experimental results are shown in figure 6:

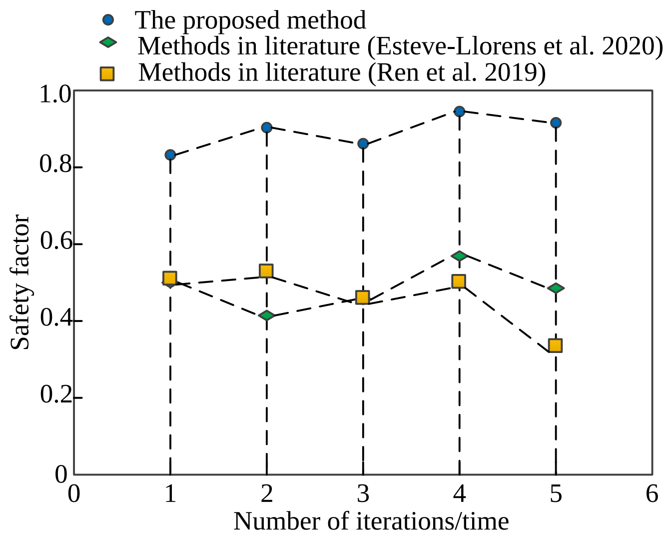

Fig. 6 Comparison of relay protection safety of different methods

It can be seen from figure 6 that under the same experimental environment, the safety factor of relay protection of multilevel differential distribution network is higher, the highest is about 0.97, and the highest safety factor of other traditional methods is about 0.59 and 0.55, respectively. This is due to the proposed method to segment the main feeder of the distribution network, to set up a contact switch at the end of the feeder, to analyze the equivalent topology of the multistage differential distribution network, to connect the first power supply to the substation, and to regard it as an ideal voltage source. Considering the area index of the switch, the greedy algorithm is used to optimize the configuration of the feeder segment switch, and then The safety of the proposed method for relay protection of multilevel differential distribution network is improved.

4.3.2 Analysis of Fault Location Error in Distribution Network with Different Methods

To further verify the scientific effectiveness of the proposed method, the experimental analysis of the proposed method, the literature (Esteve-Llorens et al. 2020) method and the error of the literature

(Ren et al. 2019) method in the fault location of the multistage differential distribution network, the experimental results are shown in figure 7:

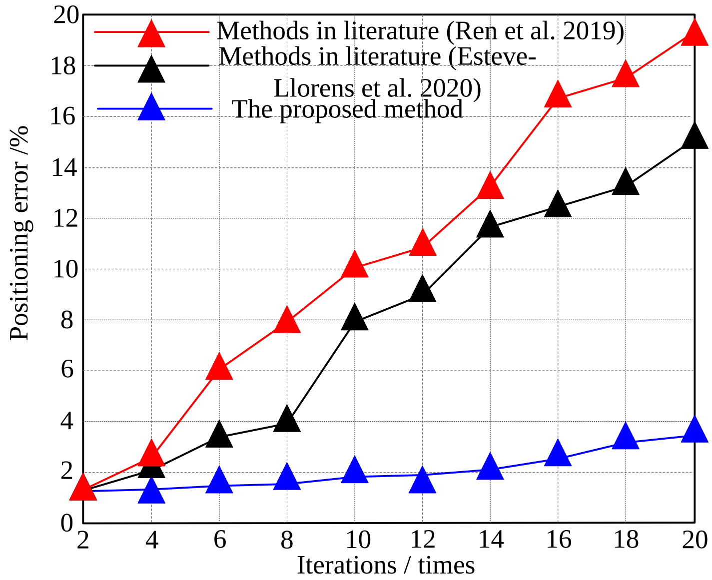

Fig. 7 Fault location error analysis of distribution network with different methods

Analysis figure 7 shows that there is a certain gap between the three methods in the error of fault location error in distribution network. Among them, the positioning error of the proposed method is lower than 4, while the error of other methods is always higher than that of the proposed method. This is due to the analysis of the protection misoperation of the multistage differential distribution network and the sensitivity of the feeder segment switch, and the realization of the relay protection of the multistage differential distribution network, which improves the positioning accuracy of the fault in the multistage distribution network and reduces the error.

5 Conclusion

In this paper, the relay protection method of multistage differential distribution network based on feeder segment switch is proposed. The main feeder of the distribution network is segmented and the contact switch is set at the end of the feeder. The equivalent topology structure of the multi-stage differential distribution network is analyzed to connect the first power supply to the substation, which is regarded as the ideal voltage source, considering the area index of the switch, using greedy algorithm to optimize the configuration of the feeder segment switch The sensitivity of line segment switch and the relay protection of multistage differential distribution network are realized. Compared with the traditional method, this method has the following advantages:

The maximum safety factor of relay protection for multistage differential distribution network is about 0.97, which has high safety and certain reliability. The proposed method is feasible for the fault location error of multistage differential distribution network is always less than 4.

Although the method of this paper is feasible at the present stage, there are still many shortcomings. In the future, the influence of multilevel difference on distribution network will be studied more deeply, and then the credibility of the article will be improved.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Conflict of interest

The authors declare no conflict of interest.

Fundings

The research is supported by Key Project of the National Natural Science Foundation of China (51637005), Research on system Security Protection based on Multi-dimensional Information Fusion of Smart Grid ,2017/01-2021/12

References

Barker KM, Subramanian SV, Berkman L (2019) Adolescent sexual initiation: A cross-classified multilevel analysis of peer group-, school-, and neighborhood-level influences. J Adolesc Health 65(3):390-396.

Boyer AP, Fair AM, Joosten YA et al (2018) A multilevel approach to stakeholder engagement in the formulation of a clinical data research network. Medical Care 56(10):22-26.

Dimitrios T, Adam D, Blair SM (2018) Centralisedbusbar differential and wavelet-based line protection system for multi- terminal direct current grids, with practical IEC-61869-compliant measurements. IET Gener Transm Distrib 12(14):3578-3586.

Duarte SN, Ghetti FT, Almeida PD et al (2019) Zero-sequence voltage compensation of a distribution network through a four-wire modular multilevel static synchronous compensator. Inter J Elect Power Ener Syst 109(7):57-72.

Esteve-Llorens X, Martin-Gamboa M, Iribarren D (2020) Efficiency assessment of diets in the Spanish regions: A multi-criteria cross-cutting approach. J Clean Prod 242(1):118-129.

Freitas NBD, Jacobina CB, Marinus NS (2018) Ac-Dc-Ac single-phase multilevel six-leg converter with reduced number of controlled switches. IEEE Trans Power Electron 33(99):3023-3033.

Karunananthan S, Moodie EE, Bergman H (2019) The association between physical function and proximity to death in older adults: a multilevel analysis of 4,150 decedents from the Cardiovascular Health Study. Ann Epidemiol 35(04):59-65.

Li H, Deng C, Zhang Z et al (2021) An adaptive fault-component-based current differential protection scheme for distribution networks with inverter-based distributed generators. Inter J Elect Power Ener Syst 128(2):106719.

Li Y, Pei X, Yang M et al (2020) An advanced fault control of transformerless modular multilevel converters in AC/DC hybrid distribution networks under the single-phase grounding fault. IEEE Trans Power Deliv (99):1-1.

Li Y, Zhang AL, Huang FQ (2019) Research on networked protection control scheme for closed loop operation distribution network. Mech Electr Eng Tech 48(02):85-89.

Rajalakshmi J, Durairaj S (2020) Application of multi-objective optimization algorithm for siting and sizing of distributed generations in distribution networks. J Comb Optim 41(2):1-23.

Rajput VN, Farhad A, Pandya KS (2018) Optimal coordination of directional overcurrent relays using improved mathematical formulation. IET Gener Transm Distrib 12(9):2086-2094.

Ren C, Liang YJ, Lu XJ (2019) Research on the soil moisture sliding estimation method using the LS-SVM based on multi-satellite fusion. Int J Remote Sens 40(5):2104-2119.

Sharma V, Salwan R, Shanmugam V (2018) Unraveling the multilevel aspects of least explored plant beneficial Trichodermasaturnisporum isolate GITX-Panog, European J Plant Pathol 152(3):1-15.

Stepanov A, Saad H, Karaagac U (2019) Initialization of modular multilevel converter models for the simulation of electromagnetic transients. IEEE Trans Power Deliv 34(1):290-300.

Twyford AD, Wong ELY, Friedman J (2020) Multi-level patterns of genetic structure and isolation by distance in the widespread plant Mimulusguttatus. Heredity 125(15):1-13.

Wang H, Zhou B, Zhang X (2018) Research on the remote maintenance system architecture for the rapid development of smart substation in China. IEEE Trans Power Deliv 33(4):1845-1852.
Yap MD, Oort NV, Nes RV (2018) Identification and quantification of link vulnerability in multi-level public transport networks: a passenger perspective. Transp 45(4):1161-1180.
Zhang J, Hu X, Xu S (2020) Fault diagnosis and monitoring of modular multilevel converter with fast response of voltage sensors. IEEE Trans Ind Electron 67(6):5071-5080.
Zhou D, Quan Z, Li Y (2020) Model predictive control of a nine-level internal parallel multilevel converter with phase-shifted pulsewidth modulation. IEEE Trans Ind Electron 67(11):9073-9082.

Qingjie Wang was born in 1982. He received the M.Sc. degree in power system and automation from North China Electric Power University (NCEPU). He is now pursuing a Ph.D. degree in NCEPU. His research interests include relay protection as well as construction, operation and maintenance of distribution systems. In recent years, he has published 10 papers, led or participated in the writing of 7 books and led or participated in a number of research projects funded by State Grid Corporation of China.