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Novel Protection Scheme of Single-phase Earth Fault for Radial Distribution Systems with Distributed Generators

Yuanyuan Wang, *Member*, *IEEE*, Gen Wei, Hongming Yang, *Member*, *IEEE*, Haowei Chen, Zi Ouyang and David J. Hill, *Fellow, IEEE*

Abstract—**This paper presents a new method based on relay agent for single-phase earth fault protection in radial distribution systems with distributed generators. In order to get the most informative fault features to discriminate fault for this system, traditional protection schemes based on different fault features are analyzed. The selection of fault features is discussed. Moreover, the cluster center of historical fault data is calculated to analyze the space distribution of fault data for each feeder by applying fuzzy clustering algorithm. The space relative distance between the on-line sample data and the cluster center and the minimum value of the space relative distance among all the relays at relay agent are obtained. Finally, the coordination strategy of relay agent is proposed to discriminate the faulty feeder. The proposed protection scheme is evaluated in a radial distribution network with distributed generations using PSCAD simulation.**

Index Terms—**Radial distribution systems, distributed generations, fuzzy clustering algorithms, single-phase earth fault protection.**

I. INTRODUCTION

In traditional distribution networks, the neutral point with non-solid earthing such as ungrounded and grounding via Petersen-coil are commonly used. For such systems, single-phase earth fault is the most common fault type [1][2]. However, the single-phase earth fault is very difficult to detect because of its low magnitude of the fault current. The protection of distribution networks must be able to reliably detect, locate and isolate single-phase earth fault before it develops into multiple-phase faults with more severe hazards. Therefore, the single-phase earth fault protection is a hot topic for research.

The increasing number of distributed generators (DGs) including the inverter-based distributed generator (IBDG) and the synchronous-based distributed generator (SBDG) has been connected to the network recently which introduces lots of new challenge to detect and locate the single-phase earth fault. For example, DGs can reduce the fault current drawn from the substation at certain locations, which makes that the fault information becomes more difficult to extract [3]. Moreover, the types of DGs can also affect the protection of distribution networks. IBDG make use of renewable. However, renewables (such as wind energy and solar energy) are intermittent in power supply, which may change the fault contribution in the line with time and cause the misjudging of the protection device [4].

Traditionally, radial networks are protected by coordinated over-current relays whereas meshed networks are protected by directional over-current relays (DOCRs) [5]. In [6], the DOCRs are improved to protect the networks with DGs. However, those approaches are only applicable on the faults with high fault currents which are hard to be applied in the protection of high-resistance single-phase earth fault. To solve the problem, the inverse time admittance (ITA) relay is presented in [7]. Here, the ITA relay utilizes the measured admittance of the protected line to identify a faulted condition in a network. The ITA relay is insensitive to fault current level. However, an excessive fault resistance can cause the error on the measured admittance which makes the protection coordination fail.

In order to improve the reliability of traditional protection methods above, several methods based on communication network were previously proposed in [8], [9] and [5]. In [8] and [9], a protection scheme measures current contribution from each source to identify fault sections then isolates faulted zone. In this scheme, the neural network algorithm is used to train the current contribution to corresponding output fault sections under different fault conditions. This scheme is affected by the penetration of DGs. In [5], a method based on relay agent (RA) is proposed to isolate a faulted segment by analyzing the sign of wavelet coefficients of the fault transient current. However, the actual performance of this method is still unpredictable. The above methods only use the single fault information like fault current which are difficult to

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Y. Y. Wang, G. Wei, H. M. Yang, H. W. Chen and D. J. Hill are with the Hunan provincial Engineering Research Center of Electric transportation and smart distributed network, the Hunan Provincial Key Laboratory of Smart Grids Operation and Control, College of Electrical and Information Engineering, Changsha University of Science and Technology, Changsha, 410114, China (e-mail: yuanyuan.wang.1980@ieee.org; 413225364@qq.com; yhm5218@hotmail.com; 445909300@qq.com; david.hill@sydney.edu.au).

Z. Ouyang is with the School of Photovoltaic and Renewable Energy Engineering, the University of New South Wales, Sydney, NSW 2052, Australia (e-mail: ouyangzi@gmail.com).

D. J. Hill is also with the School of Electrical and Information Engineering, The University of Sydney, Sydney NSW 2000, Australia, and with the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong.

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effectively restrain the effects of different fault conditions [10]. Therefore, the protection of single-phase earth fault for radial distribution systems with DGs is necessary to develop more sensitivity and reliability.

In this paper, a novel single-phase earth fault protection based on RA is presented for distribution systems with DGs. Section II briefly introduces the proposed protection framework. Section III presents the proposed feature extraction including the selection of fault feature and the data normalization. Section IV illustrates the fuzzy c-means clustering (FCM) and discusses the space relative distance. Section V demonstrates the coordination strategy of RA. Section VI presents the case study and simulation results. Section VII concludes the paper.

II. Proposed Protection Framework

RA is a computer system that is capable of managing and controlling the local relay, and as well as a reactive agent that senses the fault and sends the status signal to other RA [11][12]. The basic structure of RA is shown in Fig. 1. In the distribution systems, the RA is installed at the bus and controls at least two local relays. According to the position of other RA, RA can be divided into the upstream RA (URA) and the downstream RA (DRA). Based on the status signal of local relays and other RA, the RA can judge whether a fault occurs in the section where is protected.

The proposed protection framework based on RA is introduced in Fig. 2. It has four functions including fault detection, feature extraction, fault discrimination and RA coordination. When the protection starts, the local information of relays including voltage and current is collected for RA.

Fault detection is capable of detecting the earth fault with high resistance. Traditionally, the measurement of the zero-sequence voltage is suggested to be used for fault detection because it is very sensitive to earth faults [13]. The value of zero-sequence voltage is equal to zero in normal operation but rise to a very high level during a single-phase earth fault. This method can detect the earth fault if the amplitude of the voltage exceeds a threshold value which is 15 percent of the amplitude of normal voltage.

The feature extraction is executed after the fault has been detected. Here, the local information can be handled to extract all the fault features by using fast fourier transform algorithm (FFT), and then all fault features are normalized by the z-score method.

In the fault discrimination, the fault features are divided into the sample data and the historical fault data. The sample data is the real time data from each relay at the bus. The historical fault data is the fault data from the historical fault accident which is recorded in the tripped relay. The historical fault data can be considered a fault cluster. The fault cluster center of the historical fault data can be calculated off-line by FCM algorithms. The fault cluster center can describe the space distribution of fault data under different fault condition for each feeder. The space relative distance between the sample data and the fault cluster center is calculated by distance calculation methods for each relay, which shows the

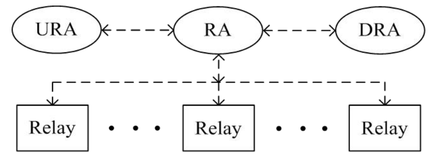

Fig. 1. The basic structure of RA

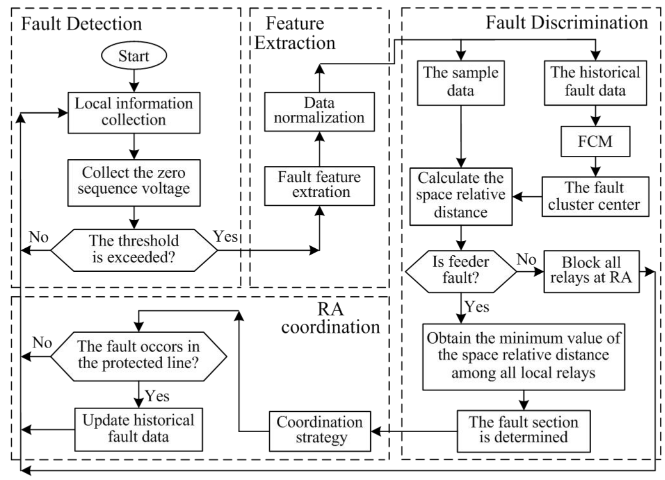

Fig. 2. The proposed protection framework based on RA

comparability measurement between the sample data and the fault data. Here, the fault types including feeder fault and bus fault can be judged due to the obvious differences in the value of the space relative distance between the feeder fault and bus fault, which will be analyzed in detail in the section VI. For feeder fault, generally speaking, the smaller space relative distance has higher possibility that the sample data belongs to the fault data. Based on this theory, comparing the distance in all relays at the bus, the smallest distance can be obtained to identify the section where the fault occurs.

However, for feeder fault, the fault section determined by the RA itself may be not the most accurate one. Therefore, the specific fault line cannot be found. In order to solve this problem, the coordination strategy of RA is proposed to determine the fault line in section V. According to the results of the fault discrimination, the coordination of RAs can effectively find out the specific fault line.

III. Feature Extraction

A. Fault Feature Selection

The proposed method is integrated with all kinds of fault features to provide an effective solution for distribution systems protection. However, different approaches based on different fault features have variable applicable ranges, fault detection robustness and accuracy [14]. Each single scheme has its own advantages and disadvantages. Therefore, for the proposed method, the most informative fault features are selected to discriminate fault.

For the radial distribution systems with DGs, the fault environments are more complex than the traditional distribution systems. In addition, more impact factors including fault resistance, fault initial angle, fault position and

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the control strategy of IBDG, etc. have to be considered after the occurrence of single-phase earth fault. For this system, different protection approaches based on different fault features are analyzed as follow:

1) The approaches based on the steady-state components such as the negative and zero sequence components including current and power. Due to the appearance of the negative sequence grid voltage during the unsymmetrical fault, the negative-sequence current and harmonics generated from IBDG can adversely affect the reliability and accuracy of the protection approaches using those fault features [15]. In addition, the approaches using zero sequence components can only be applied in the non-grounding system. These methods cannot detect fault in the Petersen-coil-grounded system due to the compensation of Petersen coil.

2) The approaches based on the transient components. The compensation of Petersen coil in a charging and discharging are not fully worked in the first 0.5 to 1 cycles when the fault occurs [16]. The voltage and current signals have different characteristics between the fault feeder and sound feeder in this period. Therefore, the transient components such as the zero-sequence transient component, the transient energy and the transient feature using wavelet transformation, etc. are widely used to overcome the effects of Petersen coil. In addition, the zero-sequence component is mainly affected by the distributed capacitance of feeder and the fault resistance, etc. and other parameters (such as output power of DG, etc.) have relatively little impact on the distribution of transient zero sequence current [17].

In this paper, the transient components based on the zero-sequence component including the magnitude and phase angles of zero-sequence current, the phase angle difference between the zero-sequence voltage and current, and the transient zero-sequence energy are selected as fault features to analyze the fault. Those fault features not only have little effects on the compensation of Petersen coil, but also can avoid the interference of DG.

B. Data Normalization

When a single phase-earth fault occurs, the selected fault features as the inputs are extracted in real time for each relay. This online data is named as sample data X'_s as follows:

$$X'_s = (x'_{s1}, x'_{s2}, \cdots, x'_{st}) \tag{1}$$

where t is the number of fault feature for each data.

The historical fault data are recorded off-line for each relay, and defined as follows:

$$X'_f = \begin{bmatrix} x'_{11}, x'_{12}, \cdots, x'_{1t} \\ x'_{21}, x'_{22}, \cdots, x'_{2t} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ x'_{n1}, x'_{n2}, \cdots, x'_{nt} \end{bmatrix} \tag{2}$$

where n is the number of data.

In the proposed method, the sample data X'_s calculates the space relative distance with historical fault data X'_f for fault discrimination. Therefore, the sample data X'_s need consider the effects of the historical fault data X'_f. The data set X' including sample data X'_s and the historical fault data X'_f is defined to as follows:

$$X' = \begin{bmatrix} X'_s \\ X'_f \end{bmatrix} = \begin{bmatrix} x'_{s1}, x'_{s2}, \cdots, x'_{st} \\ x'_{11}, x'_{12}, \cdots, x'_{1t} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ x'_{n1}, x'_{n2}, \cdots, x'_{nt} \end{bmatrix} \tag{3}$$

For different fault features, the above data have different scales and different effects on the process of fault analysis. In order to guarantee the reliability of the results, it is necessary to carry out the normalization of the raw data. Data normalization can transform the raw data into the normalized data with same proportional scale. There are many methods for data normalization. The z-score method, a most common normalization method, is very useful when the minimum and maximum values among data are unknown [18]. The z-score method based the mean and standard deviation of data is defined as follows:

$$x_{kj} = \frac{x'_{kj} - \bar{x}'_j}{S(x'_j)}, 1 \le k \le n, \quad 1 \le j \le t \tag{4}$$

$$\bar{x}'_j = \frac{1}{n}\sum_{k=1}^{n} x'_{kj} \tag{5}$$

$$S(x'_j) = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x'_{kj} - \bar{x}'_{kj})^2} \tag{6}$$

where x_{kj} is the normalized pattern value, $\bar{x}'_j$ is the mean value of the jth fault feature, $S(x'_j)$ is the standard deviation of the jth fault feature.

The historical fault data X'_f is normalized using the function (4)-(6) and then transformed into the normalized historical fault data X_f. Similarly, considering the effects of historical fault data X'_f, the normalized sample data X_s will be obtained by the above normalization process of data set X'.

IV. Fault Discrimination

Intelligent algorithms such as Neural Network algorithm [8][9], are widely applied for fault discrimination to discriminate between the fault data and the non-fault data for the real-time sample data. In the proposed method, the spatial distribution regularities of historical fault data are analyzed by FCM algorithm. The sample data are an unknown data. It could be a fault data or a non-fault data. The sample data can be judged as a fault data if it is followed the distribution regularities. In this section, the space relative distance as a comparability measurement (or similarity measurement) between the sample data and the fault data will be introduced.

A. FCM Algorithm

Fuzzy clustering plays an important role in pattern recognition and data analysis. The FCM algorithm is one of the best known fuzzy clustering methods. In FCM, each data is

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assigned a membership to represent the degree of belonging to a certain class (or cluster) [19]. The normalized historical fault data set X is given as a certain cluster to calculate the cluster center by the FCM algorithm. The objective function of the clustering optimization is shown as below:

$$J_m(U,P)=\sum_{k=1}^{n}\sum_{i=1}^{c}\mu_{ik}^{m}\|x_k-p_i\|^2, m\in[1,\infty) \quad (7)$$

where $U=[\mu_{ik}]_{c\times n}$ is membership function matrix and μ_{ik} is the membership value of data x_k for cluster i, $p_c=(p_{c1},p_{c2},...,p_{ct})$ is cluster center and $c\in[1,n]$ is the number of clusters, m, greater than 1, is fuzzifier that controls the amount of fuzziness in fuzzy classification, k is the number of data.

The FCM algorithm can be mainly divided into three steps:

Step 1: Give the number of clusters c and the fuzzifier m. c is set as 1 and m is set as 2. Then membership function matrix U is initialized and satisfied as follows:

$$\mu_{ik}\in[0,1]\forall i,k;\ \sum_{i=1}^{c}\mu_{ik}=1,\forall k;\ 0\le\sum_{k=1}^{n}\mu_{ik}\le n,\forall i \quad (8)$$

Step 2: Calculate a new cluster centers p_i and membership μ_{ik} as below:

$$p_i=\frac{\sum_{k=1}^{n}(\mu_{ik})^m\cdot x_k}{\sum_{k=1}^{n}(\mu_{ik})^m} \quad (9)$$

$$\mu_{ik}=\frac{\left(1/\|x_k-p_i\|^2\right)^{1/(m-1)}}{\sum_{k}^{c}\left(1/\|x_k-p_i\|^2\right)^{1/(m-1)}},\quad 1\le i\le c,\ 1\le k\le n \quad (10)$$

Step 3: According to the new cluster centers p_i and membership μ_{ik}, calculate the value of the objective function $J_m(U,P)$ based on (7). When the obtained value is less than the minimum amount of improvement (set as 1e-5), stop the process of FCM algorithm, and otherwise go back to the step 2.

Through the above processes of FCM algorithm, the cluster center of historical fault data set can be calculated. In the proposed method, the cluster center has a clear physical meaning. It comprehensively describes the distribution of fault data under different condition for each feeder [20].

B. Space Relative Distance

Similarity measurement is an important indicator to describe the closeness degree between the simple data and the fault cluster center. The distance methods are one of the most common calculation methods. They indicate the space relative distance between the nearby data and the remote data. The nearby data has similar characteristics and the remote data has great difference. When a fault occurs, the space relative distance between the normalized sample data X_s and the cluster center p_i of historical fault data is calculated by distance methods for fault discrimination. The distance methods are introduced as follows:

1) Euclidean distance:

$$d_{kj}^2=\sum_{j=1}^{t}\left(x_{kj}-p_{kj}\right)^2 \quad (11)$$

2) City block metric distance:

$$d_{kj}=\sum_{j=1}^{t}\left|x_{kj}-p_{kj}\right| \quad (12)$$

3) Chebyshev distance [21]:

$$d_{kj}=\lim_{z\to\infty}\left(\sum_{j=1}^{t}\left|x_{kj}-p_{kj}\right|^z\right)^{1/z}=\max\left|x_{kj}-p_{kj}\right| \quad (13)$$

Due to different calculation principles, the space relative distance based on different distance methods have different results for fault discrimination. Therefore, it is necessary to compare all distance methods to find out the optimal one for the proposed method.

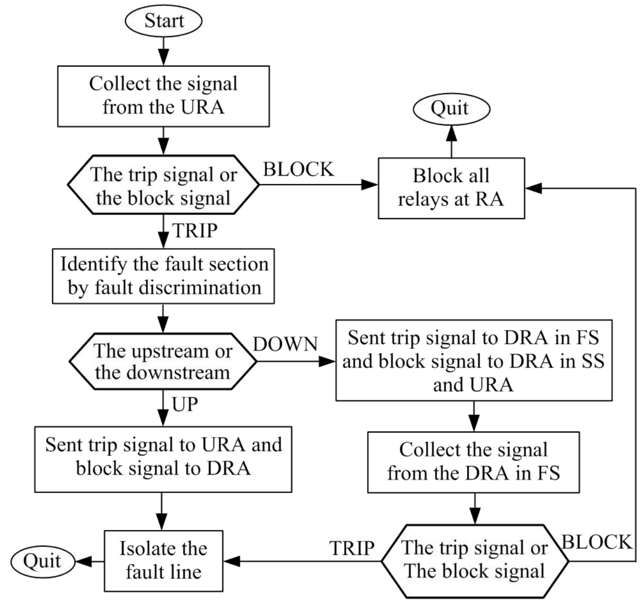

Fig. 3. Structure of coordination strategy

V. RA COORDINATION

RA is a protection system that not only autonomously collects the local information to detect fault but also cooperate with other RAs for fault discrimination. When a feeder fault occurs, the results of fault discrimination are divided into the fault section (FS) and sound section (SS) for each feeder which are connected with the RA. The fault section is defined as the section protected by the relay with the minimum value of space relative distance. The sound section is defined as the section protected by the relay with the greater value of space relative distance. The coordination strategy of RA is shown as Fig. 3. According to the different sections, the RA will sent different status signals to the adjacent RA including URA and

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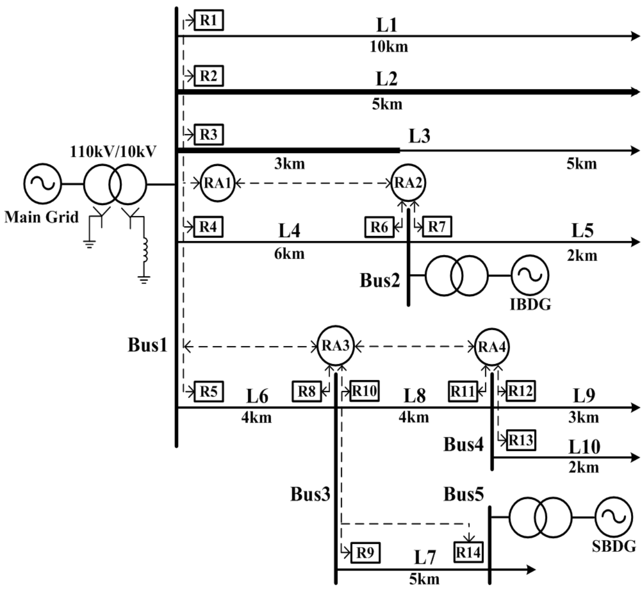

Fig. 4. The Studied System Model for Simulation

TABLE I
FEEDER PARAMETERS

	Overhead line			Cable line		
	R	X_L	X_C	R	X_L	X_C
Positive sequence	0.45	0.5385	34979	0.27	0.08	7981.74
Zero sequence	0.7	1.2273	83766	2.7	0.32	11373.98

Note：the unit of feeder parameters is Ω/km

DRA. The signals include trip signals and block signals. The trip signals are sent to adjacent RA where a fault may occur. In contrast, the block signals denote that the section protected by RA is sound and the RA needs to block all relays.

In the coordination strategy, the RA closed to the main grid has a priority to execute the coordination strategy which can send the signal to DRA. Then the DRA also sent the signal to the URA due to the results of fault discrimination. RA can be cooperated to locate the exact fault line from top to bottom of the main grid.

VI. SIMULATION ANALYSIS

A. Simulation Model

A radial distribution systems (10 kV and 50 Hz) grounded by Petersen-coil as shown in Fig. 4 is simulated using PSCAD. The feeders including the overhead line (the fine lines such as L1), the cable line (the bold lines such as L2) and the hybrid transmission line including overhead line and cable line (such as L3) are considered in this system. The feeder parameters including resistance R , inductive reactance X_L and capacitive reactance X_C for positive sequence and zero sequence are shown in Table I. The Petersen coil grounding method with 110% degree of compensation is used, and the Petersen coil inductance is set as 0.83 H.

There are 14 relays in this system used to protect the feeder. And the system has four RAs installed at different buses to control and manage the local relays centrally. The communication lines (the dash lines shown in Fig. 4) assumed as a perfect state in this paper, connect the RA and relay as well as the RA and other RAs. In addition, the interconnection of IBDG and SBDG to the system is considered as Fig 1. In this system, a 3-MW IBDG using PQ control strategy is connected to the bus 2, and is considered the random change of its supply. A 2.7-MW SBDG is connected to the bus5 on a far right end of the system, and is assumed as full-power operation. The loads are modeled by constant impedances, which are represented by arrows shown in Fig. 4.

This paper only considered the fault occurs in the feeder and the bus. The situation of fault occurred in the inside of DG is out of the scope of this paper.

TABLE II
CLUSTER CENTER OF HISTORICAL FAULT DATA FOR ALL RELAYS

Cluster center	Fault feature			
p_{f1}	-0.2892	0.1427	0.1663	0.2625
p_{f2}	-0.2951	0.2091	0.1896	0.3633
p_{f3}	-0.2225	0.1574	0.1797	0.1358
p_{f4}	-0.0835	0.4027	-0.5974	0.1739
p_{f5}	-0.2323	0.0412	-0.593	0.1803
p_{f6}	0.2361	-0.2056	-0.0222	0.2906
p_{f7}	0.2401	-0.5818	0.0405	0.2891
p_{f8}	0.2511	0.4643	-0.174	0.1898
p_{f9}	-0.4853	-0.1385	0.0448	0.0489
p_{f10}	-0.3513	-0.1052	0.0443	0.0021
p_{f11}	0.2669	0.0219	-0.1892	0.1523
p_{f12}	-0.3336	-0.0199	0.0803	0.2487
p_{f13}	-0.3248	-0.0527	0.0698	0.3382

B. Generation of Historical Fault Data

In this simulation test, the historical fault data is generated by simulating different fault conditions beforehand. All the fault conditions are assumed to be occurred at phase A of each feeder. The beforehand fault conditions are shown as follows:

a) fault resistance R_f: 1Ω, 50Ω, 150Ω, 300Ω and 500Ω;

b) fault initial angle δ : 0°, 45° and 90°;

c) the percent of the position L_f from the fault point to the far left end of each feeder: 10%, 50% and 90%.

d) the percent of the output power S of IBDG: 50% and 100%.

Under above fault conditions, the data of each phase voltage and current for all relays are recorded by PSCAD where the data sampling rate is set as 4000Hz. The recorded data are input into the Matlab software to normalize by z-score method and extract the fault features which constitutes the history fault data of each relay. Then the fault cluster centers of each relay shown in Table II are calculated by FCM algorithm in Matlab.

In Table II, the cluster centers p_{f1} - p_{f13} are corresponding to the historical fault data of the relays R1-R13 respectively. Each cluster enter has four variables such as the phase angle of zero-sequence current, the phase angle difference between the zero-sequence voltage and current, the magnitude of zero-sequence current and the transient zero-sequence energy.

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TABLE III
THE SPACE RELATIVE DISTANCE USING CITY BLOCK METRIC DISTANCE METHOD UNDER DIFFERENT FAULT CONDITIONS FOR ALL RELAYS

Fault	Fault conditions				RA1					RA2		RA3			RA4		
	$R_f(\Omega)$	δ (°)	L_f(%)	S (%)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13
$F1$	1	0	5	0	**4.32**	16.7	18.03	18.76	19.79	-	-	-	-	-	-	-	-
$F2$	50	15	10	10	20.8	**1.83**	18.41	18.81	19.97	-	-	-	-	-	-	-	-
$F3$	100	30	20	20	20.86	16.92	**0.89**	18.8	19.96	-	-	-	-	-	-	-	-
$F4$	200	60	30	40	20.80	16.78	18.34	**1.18**	19.96	**3.19**	20.03	-	-	-	-	-	-
$F5$	400	90	40	50	20.62	16.37	17.92	**1.45**	19.77	23.02	**3.08**	-	-	-	-	-	-
$F6$	600	95	50	60	20.56	16.37	17.79	18.63	**2.82**	-	-	**3.14**	21.12	12.31	-	-	-
$F7$	800	105	60	70	20.66	16.35	17.83	18.73	**4.04**	-	-	15.15	**4.89**	12.39	-	-	-
$F8$	1000	120	70	80	20.43	15.65	17.44	18.54	**4.09**	-	-	14.54	20.94	**3.63**	**5.94**	20.54	21.01
$F9$	1200	150	80	90	20.16	15.73	17.03	18.39	**4.66**	-	-	14.25	20.7	**4.43**	16.97	**4.5**	20.85
$F10$	1500	180	90	100	20.32	16.61	17.39	18.85	**4.32**	-	-	14.58	21.07	**3.38**	17.12	20.66	**3.55**

Note: there are only shown the data of the RA which are needed to coordinate the URA or DRA for fault location.

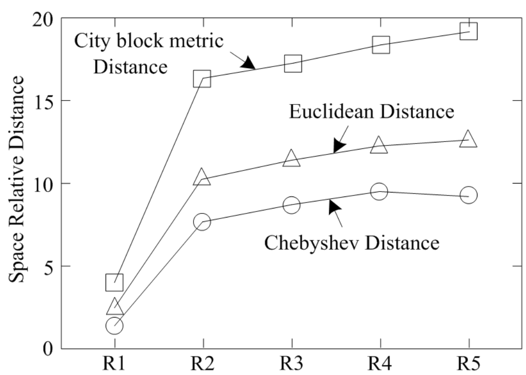

Fig. 5. The space relative distance based on different distance calculation methods during the occurrence of fault F1

TABLE IV
THE SPACE RELATIVE DISTANCE USING CITY BLOCK METRIC DISTANCE METHOD UNDER BUS FAULT AT BUS1 FOR RA1

Fault conditions		RA1					
	S (%)	R1	R2	R3	R4	R5	Δd_{RA}
	100	20.66	17.01	17.87	18.71	19.81	3.65
	50	20.7	17.09	17.95	19.04	19.81	3.61
	0	20.66	17.01	17.87	18.99	19.77	3.65
Switching off Feeder L1	100	-	17.09	17.99	18.92	19.83	2.74
	50	-	17.16	18.06	18.96	19.86	2.7
	0	-	17.1	17.99	18.92	19.83	2.73

C. Identification for Feeder Fault

When a single-phase earth fault F1 (R_f =1Ω, $\delta = 0^{\circ}$ and S=0%) occurs at the 5% length of the feeder L1, the real-time and local fault data collected by the relay R1 are considered as a sample data X_{s1}. The space relative distance between the sample data X_{s1} and the cluster center p_{f1} is calculated by distance calculation methods. The different distance calculation methods based on Euclidean distance method, City block metric distance method and Chebyshev distance method can obtain different results shown in Fig. 5 for the space relative distance.

From Fig. 5, the space relative distances of the different relays (such as R1, R2,…, R5) to RA1 are compared when the fault F1 happens. For fault F1, the fault feeder is L1. The space relative distances of relay R1 is the minimum value among the relays connected the RA1, which can identify the faulty feeder reliably. However, the space relative distances using City block metric distance method have the bigger difference between the fault feeder and the healthy feeder, which means that it has enough protection capability. This result also applies to other fault conditions in other feeders.

Considered the single-phase earth faults F1-F10 with different fault conditions occurred in the feeders L1-L10 respectively, the space relative distance using City block metric distance method for all relays are shown in Table III. As seen in Table III, all the minimum value among the relays connected each RA are marked as bold one. In addition, according to the coordination strategy of RA shown in Fig. 3, the tripped relays are marked with an underline during the appearance of fault.

Based on the simulation results shown above, we can see that the proposed method can reliably identify and isolate the fault line by use of relay agent. For instance, when the fault F10 occurs, the RA1 firstly starts the process of fault discrimination. The result shows that the space relative distance of R5 is the minimum value and the fault section is identified as the feeder L5 or its downstream area. Then the RA1 sends the block signal to RA2 and the trip signal to RA3. According to the received signal, the RA2 will block all relays under its control, and the RA3 will execute the same process what RA1 performed. Through above the process, the fault line is accurately determined as the feeder L10 and the relay R13 is tripped.

D. Identification for Bus Fault

Table IV shows the space relative distance of the relays connected to RA1 when the single-phase earth faults

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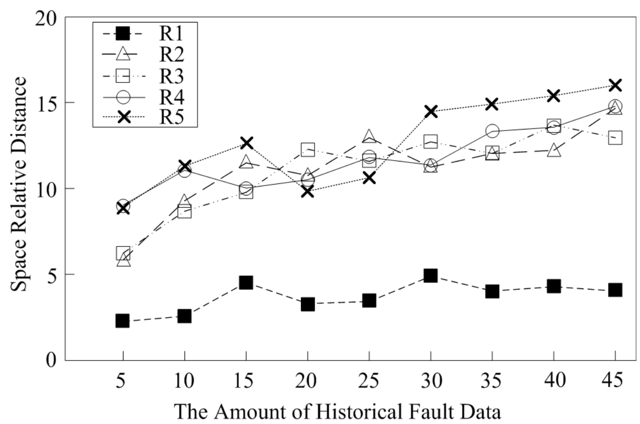

Fig. 6. The space relative distance using City block metric distance method for relays R1-R5 which are considered the different amount of historical fault data during the occurrence of fault

(R_f=500Ω and $\delta = 0^\circ$) occurred at the bus 1. The bus faults consider the variation of loading condition (switching off feeder L1) and output power S of IBDG. Compared with the data of all feeder faults shown in Table III for RA1, Table IV has the smaller difference among the data during the bus fault. Thus, the difference Δd_{RA} of the space relative distance can be defined by

$$\Delta d_{RA} = d_{\max} - d_{\min} \quad (14)$$

where the $d_{\max}$ is the maximum value among the relays connected RA and the $d_{\min}$ is the minimum value among the relays connected RA.

From the Table III and Table IV, for RA1, the range of Δd_{RA} is from 2.7 to 3.65 during the bus faults and the range of Δd_{RA} is from 8.83 to 15.23 during the feeder faults. There are obvious differences in Δd_{RA} between the bus fault and feeder fault. Thus, a threshold $\Delta d_{threshod}$ is defined to identify bus fault. When the Δd_{RA} for RA is less than the $\Delta d_{threshod}$, the fault type is identified as bus fault for RA, and all relays connected to RA are tripped. On the contrary, the fault type is identified as feeder fault when the Δd_{RA} is more than the $\Delta d_{threshod}$.

E. Effect of Historical Fault Data

The fault cluster center can effectively reflect the distributed situation of fault data for each feeder. In addition, the reliability can be improved further with increasing the amount of the available history fault data. However, in some practical situations, the amount of the available history fault data is not enough to support the need of the existing protection methods based on the intelligent algorithm such as neural network algorithm which need to have enough training samples. Therefore, the effects of the amount of historical fault data need to be considered in this paper.

Fig. 6 shows the space relative distance using City block metric distance method for relays R1-R5 which are considered the different amounts of historical fault data when the fault (R_f =1Ω, $\delta = 0^\circ$, L_f=5%, S=100%) occurs in L1. It reflects that the more historical fault data and the better the proposed method performed. In addition, the protective margins of the proposed method in practical situation are enough to meet the needs with a few data.

F. Comparison

In radial distribution systems, the DG's fault contribution may be same when the faults occur in the different feeders that are connected in parallel with same parameters. For this fault scenario, the methods (in [8][9]) based on current contribution of sources may be misjudged the fault line. In contrast, the proposed method using four fault features to determine fault can avoid it. Considering feeder L2 with the same parameters as feeder L1, the simulation results are shown in Table V when the faults happen in L1 and L2 , respectively, for the proposed method. In Table V, the difference of the space relative distance among the relays (R3, R4, R5) is small under different fault points, and it can deem that the current contribution from each source is nearly equal for R1 and R2. According to the simulation results, comparing the method based on the current contribution of sources, the proposed method has higher reliability for the faults happened in the different feeders with same parameters.

TABLE V
THE SPACE RELATIVE DISTANCE USING CITY BLOCK METRIC DISTANCE METHOD UNDER DIFFERENT FAULT POINTS

Fault conditions					RA1				
Fault point	R_f(Ω)	δ (°)	L_f(%)	S (%)	R1	R2	R3	R4	R5
L1	200	0	50	100	**2.31**	20.87	18.14	18.89	20.08
L1	400	0	50	100	**2.91**	19.72	18.23	18.84	20.18
L1	800	0	50	100	**3.38**	21	18.09	19.04	20.18
L2	200	0	50	100	20.75	**2.31**	18.14	18.89	20.08
L2	400	0	50	100	20.81	**2.96**	18.13	18.93	20.15
L2	800	0	50	100	20.75	**3.48**	18.09	19.06	20.18

Note: there are only shown the data of the RA which are needed to coordinate the URA or DRA for fault location.

VII. CONCLUSION

A novel protection method based on RA has been proposed in this paper to improve the protection performance of traditional methods in the single-phase earth fault protection for radial distribution systems with DGs. Its specific merits are as follows:.

1) The space relative distance based on different distance methods are compared to find out the optimal one for the proposed method. The result shows that the space relative distances using City block metric distance method is the best method to find the difference between the sample data and the historical fault data.

2) The simulation results show that the proposed protection method has desired performances under the line and bus faults with variable fault condition including the variation of loading condition and output power of DG.

3) The more historical fault data are collected, the better the proposed method performed. The fault cluster of historical fault data can better under the more fault data reflected different fault conditions for each feeder. In addition, the proposed method can discriminate fault under new fault conditions, which is not included in historical fault data.

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Yuanyuan Wang (S'12-M'15) received the B.S. and M.Sc degree in electrical engineering from Changsha University of Science and Technology, China, in 2004 and 2007 respectively, the Ph.D. degree in electrical engineering from the College of Electrical Engineering, Guangxi University, Guangxi, China, in 2012.

Now she is an Associate Professor with the College of Electrical and Information Engineering, Changsha University of Science and Technology. Her research interests are power system protection and control.

Gen Wei received B.S degree in electrical engineering from Xi'an Polytechnic University, Xi'an, China, in 2014. He is currently working toward the M.S. degree in electrical engineering in the College of Electrical and Information Engineering, Changsha University of Science and Technology, Changsha, China.

His research interests are power system protection and control.

Hongming Yang (M'12) received her M.Sc. Degree in electrical engineering from Wuhan University in 1997, and received her Ph.D. degree in electrical engineering from Huazhong University of Science and Technology in 2003.

She was a Research Associate at the Hong Kong Polytechnic University during 2009–2010, a visiting scholar in North Carolina State University during 2010–2011, and a Research Fellow at the University of Newcastle during 2013–2014. Currently, she is a fully Professor at Changsha University of Science and Technology. Her research interests include power system analysis and power markets.

Haowei Chen received B.S degree in electrical engineering from Hubei Institute for Nationalities, Huanggang, China, in 2015. He is currently working toward the M.S. degree in electrical engineering in the College of Electrical and Information Engineering, Changsha University of Science and Technology, Changsha, China.

His research interests are power system protection and control.

Zi Ouyang (M'11) received his PhD at the University of New South Wales Australia and Bachelor in Physics at Nanjing University, China. He is currently Research Fellow at School of Photovoltaic and Renewable Energy Engineering, UNSW Australia. Prior to his current position, he was a post-doctoral fellow in Swinburne University of Technology Australia, conducting research for Suntech Power.

His research interests are photovoltaic and energy storage technologies for on-grid and off-grid systems.

David J. Hill (M'76-SM'91-F'93-LF'14) received the Ph.D. degree in electrical engineering from the University of Newcastle, Australia, in 1976.

He holds the Chair of Electrical Engineering in the Department of Electrical and Electronic Engineering at the University of Hong Kong. He is also a part-time Professor of Electrical Engineering at The University of Sydney,

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Australia. During 2005-2010, he was an Australian Research Council Federation Fellow at the Australian National University. Since 1994, he has held various positions at the University of Sydney, Australia, including the Chair of Electrical Engineering until 2002 and again during 2010 - 2013 along with an ARC Professorial Fellowship. He has also held academic and substantial visiting positions at the universities of Melbourne, California (Berkeley), Newcastle (Australia), Lund (Sweden), Munich, Hong Kong (City and Polytechnic). His general research interests are in control systems, complex networks, power systems and stability analysis. His work is now mainly on control and planning of future energy networks and basic stability and control questions for dynamic networks.

Prof. Hill is a Fellow of the Society for Industrial and Applied Mathematics, the Australian Academy of Science, and the Australian Academy of Technological Sciences and Engineering. He is also a Foreign Member of the Royal Swedish Academy of Engineering Sciences.

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