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Approximate Entropy Based Fault Localization and Fault Type Recognition for Non-solidly Earthed Network

Qingle Pang[1], Xinyun Liu[1], Bo Sun[2], Qunli Ling[1]

[1]School of Information and Electronic Engineering, Shandong Institute of Business and Technology, Yantai 264005, China, stefam@163.com
[2]School of Control Science and Engineering, Shandong University, Jinan, 250061, China, sunbo@sdu.edu.cn

For non-solidly earthed network, the fault localization of single phase grounding fault has been a problem. A novel fault localization and fault type recognition method of single phase grounding fault based on approximate entropy is presented. The approximate entropies of transient zero sequence current at both ends of healthy section are approximately equal, and the ratio is close to 1. On the contrary, the approximate entropies at both ends of fault section are different, and the ratio is far from 1. So, the fault section is located. At the same fault section, the smaller is the fault resistance, the larger is the approximate entropy of transient zero sequence current. According to the function between approximate entropy and fault resistance, the fault type is determined. The method has the advantages of transferring less data and unneeded synchronous sampling accurately. The simulation results show that the proposed method is feasible and accurate.

Keywords: Approximate entropy, fault localization, fault type recognition, non-solidly earthed network

1. INTRODUCTION

MANY DISTRIBUTION networks often adopt neutral non-solidly earthed system, including non-earthed or neutral earthed via Peterson coil [1]. The probability of single phase grounding fault for neutral non-solidly earthed system is very high. Because of the small fault current, the fault localization is difficult. Now, the fault detection technology for single phase grounding fault in neutral non-solidly earthed system is basically mature, but the fault localization problem has not been solved. The current fault localization method for single phase grounding fault in neutral non-solidly earthed system mainly includes the power frequency current amplitude comparison method [2], the phase comparison between zero sequence current and zero sequence voltage method [3], the signal injection method [4] and the traveling wave method [5]. The power frequency signal methods are not applicable to the distribution network with distributed generator. The signal injection method needs to install signal injection device in power system. The traveling wave method can be only applied to the distribution networks with less feeder branches. At the same time, traveling wave is difficult to detect. When a single phase grounding fault occurs, the amplitude of transient fault signal is large and is not affected by the Peterson coil. It is applicable to the neutral earthed via Peterson coil.

With the development of electronic technology, the wave record and real time data processing for transient signal is easy to realize. The transient signals have been applied to fault detection technology and achieved very good results [6], [7]. The reference [8] proposed a fault localization method based on approximate entropy of zero-mode power, but the zero-mode voltage and zero-mode current must be detected to calculate the approximate entropy of zero-mode power. The paper applies the transient zero-sequence current signal to fault localization for neutral non-solidly earthed system, devises a novel fault localization and fault type recognition method based on approximate entropy of transient zero sequence current, and verifies its correctness and efficiency through ATP simulation.

2. STRUCTURE OF INTELLIGENT FEEDER AUTOMATION

In the smart distribution grid, the intelligent feeder automation can use the information interaction to realize its self-heal function. The structure of the intelligent feeder automation is designed as shown in Fig.1. It mainly consists of a master station, feeder terminal unit (FTU) and the communication network based on the TCP/IP protocol. The master station and the FTUs are constructed into a distributed control system via optical Ethernet. The FTUs can detect fault and process the fault information. Through the communication network, the FTUs upload the fault information processing results to the master station. The master station determines the fault localization and fault type according to the uploading fault information, and it sends remote trip commands to the FTUs of both ends of the fault localization section, so the fault localization and fault isolation can be realized. The master can fulfill fault restoration according to the fault area and network topology. The paper focuses on the study of fault localization and fault type recognition method.

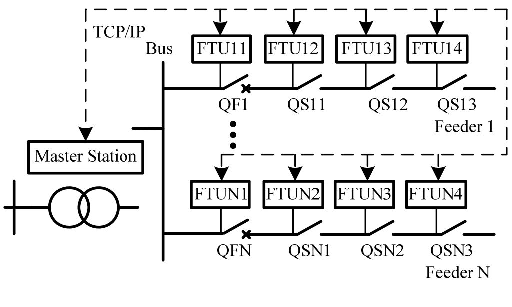

Fig.1. Structure of intelligent feeder automation

3. FAULT LOCALIZATION AND FAULT TYPE RECOGNITION BASED ON APPROXIMATE ENTROPY

A. Approximate Entropy Theory

Approximate entropy (ApEn) is a dimensionless index to measure the complexity of time series. It was proposed by Pincus from the perspective of time series complexity in early 1990s [9], [10]. Approximate entropy is to measure the complexity of time series. The more complex the time series, the larger its approximate entropy, and it is independent of the absolute amplitude of time series. Because approximate entropy needs a short data window and is applicable to random signal and deterministic signal, it is widely used in medicine, biology and fault diagnosis of mechanical equipment and other fields [11]-[13]. Fu Ling introduced approximate entropy into the field of fault detection for power system, and successfully applied approximate entropy to the feature extraction of fault signals for neutral non-solidly earthed system [14].

B. Approximate Entropy Algorithm

The approximate entropy algorithm steps for an original time series $\{u(i), i=1, 2, \ldots, N\}$ are as follows:

a. Given dimension m, using the original time series, construct a set of m dimensional vector $X(1), X(2), \ldots, X(N-m+1)$, where

$$X(i) = \{u(i), u(i+1), \ldots, u(i+m-1)\} \quad i = 1,2,\ldots, N-m+1 \tag{1}$$

b. Calculate the Euclidean distance between any vector $X(i)$ and the rest of vectors $X(j)$:

$$\mathrm{d(i,j)} = \max_{\mathrm{k}=0,1,\ldots,\mathrm{m}-1}\left[\left|\mathrm{x(i+k)} - \mathrm{x(j+k)}\right|\right] \tag{2}$$

c. Given a tolerance threshold r, count the number $N^m(i)$ to meet $d(i, j)<r$ for each vector $X(i)$, and calculate the ratio $C_i^m(r)$ between the number $N^m(i)$ and the total number of vectors.

$$C_i^m(r) = \frac{N^m(i)}{N-m+1} \tag{3}$$

d. Calculate the logarithm of $C_i^m(r)$, then calculate their average value $\Phi^m(r)$ for all i as follows:

$$\Phi^{\mathrm{m}}(\mathrm{r}) = \frac{1}{\mathrm{N-m+1}}\sum_{\mathrm{i}=1}^{\mathrm{N-m+1}} \ln \mathrm{C}_{\mathrm{i}}^{\mathrm{m}}(\mathrm{r}) \tag{4}$$

e. After m increases by 1, repeat steps a-d to obtain $\Phi^{m+1}(r)$.

f. The approximate entropy of the original time series is calculated as follows:

$$ApEn(m, r, N) = \Phi^m(r) - \Phi^{m+1}(r) \tag{5}$$

Pincus suggested taking m=2 and r=0.1~0.2σ, where σ is the standard deviation. The paper takes m=2 and r=0.15σ.

C. Principle of Fault Localization Based on Approximate Entropy

In the actual distribution network, the feeder terminal units (FTUs) or other fault detection devices are installed at the detection points along feeders. When a single phase grounding fault is detected, FTUs storage the transient zero sequence current signals and calculate their approximate entropies, then they upload the approximate entropies to the master station. The master station calculates the ratio between the approximate entropies of adjacent detection points (the ratio of the smaller value to the larger value). If the ratio is close to 1 (more than 0.75), the section between the two detection points is healthy section. If the ratio is far from 1 (less than 0.75), the section between the two detection points is fault section. So the fault section localization can be realized.

For the actual distribution networks, a large number of simulation experiments of single phase grounding fault are carried out. For each section, the approximate entropies of transient zero sequence currents are calculated when fault resistances change. So the function between the approximate entropies of transient zero sequence current and fault resistances is obtained.

$$R_k = f_p(ApEn(p)) \tag{6}$$

Where R_k represents the fault resistance, $ApEn(p)$ represents the approximate entropy of transient zero sequence current in section p, $f_p(\cdot)$ represents the function between $ApEn(p)$ and R_k. The master station calculates the approximate entropy of the transient zero sequence current at the upstream point of the fault section and substitutes the value into the formula (6). The forecasting fault resistance can be obtained and the fault type is recognized.

4. SIMULATION VERIFICATION

A. Simulation Model

Using the Alternative Transients Program EMTP/ATP, a large number of simulation experiments were done to verify the correctness and efficiency of the proposed method. The distribution network model is shown in Fig.2. For the parameters of the model see reference [15].

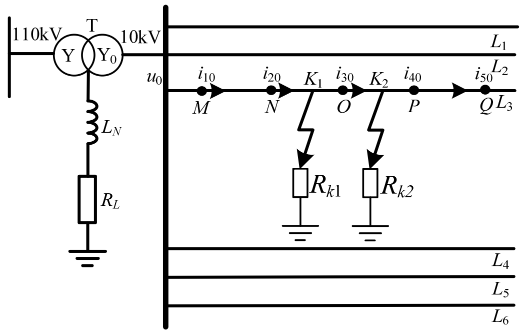

Fig.2. Distribution network model

B. Fault Localization Verification

It is supposed that the fault section is *NO* section in L_3 and the earthed resistance is 10Ω, the fault angle is 90º. The zero sequence voltage *u*0 and the zero sequence currents *i*10, *i*20, *i*30, *i*40, *i*50 of the detection points *M*, *N*, *O*, *P* and *Q* are shown in Fig.3 (a)-(f). The half cycle transient zero sequence current from fault starting time is regarded as the original time series. According to the algorithm of section 2.2, the approximate entropy of each transient zero sequence current is calculated. The approximate entropies and the ratios between the adjacent detection points are shown in Table 1. From the table, the ratio between detection points *N* and *O* is less than 0.75. So the section *NO* is fault section. Other ratios are all bigger than 0.75. The other sections are all healthy sections. The fault localization results are correct.

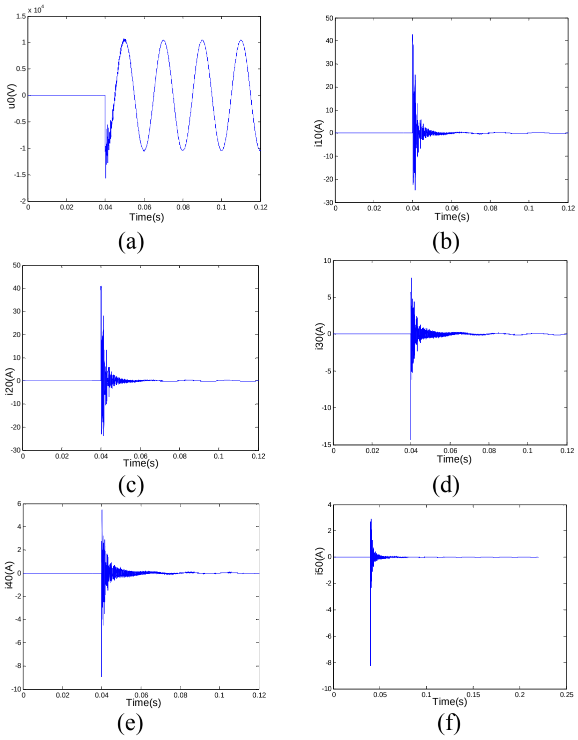

Fig.3. Zero sequence voltage and zero sequence current

Table 1. Approximate entropies of every detection point

	*i*10	*i*20	*i*30	*i*40	*i*50
ApEn	0.356	0.3543	0.6637	0.633	0.7626
Ratio	0.9952	0.5338	0.9537	0.8301	
Fault	No	Yes	No	No	

C. Comparison with other methods

In order to show the advantages of the fault localization method based on approximate entropy, many simulation experiments have been done to compare with the power frequency zero sequence current amplitude comparison method. The results show that the localization effects of these two methods are the same for traditional radial grid. For the smart grid with distributed generators, the power frequency current amplitude comparison method cannot locate the fault position correctly, however, the proposed method can achieve the correct fault position.

In Fig.2, the distributed generator is located at node P of L3. It is supposed that the fault section is NO section in L3 and the earthed resistance is 20Ω, the fault angle is 90º. The steady state zero sequence currents i10, i20, i30, i40, i50 of the detection points M, N, O, P and Q are shown in Fig.4 (a)-(e). The power frequency zero sequence current amplitudes and the ratios between the adjacent detection points are shown in Table 2. From the table, the ratio between detection points P and Q is the smallest and the section PQ is fault section. The localization result is wrong. The approximate entropies and the ratios between the adjacent detection points are shown in Table 3. From the table, the fault section is the section NO. The localization result is true. So this method has an obvious advantage for smart grid.

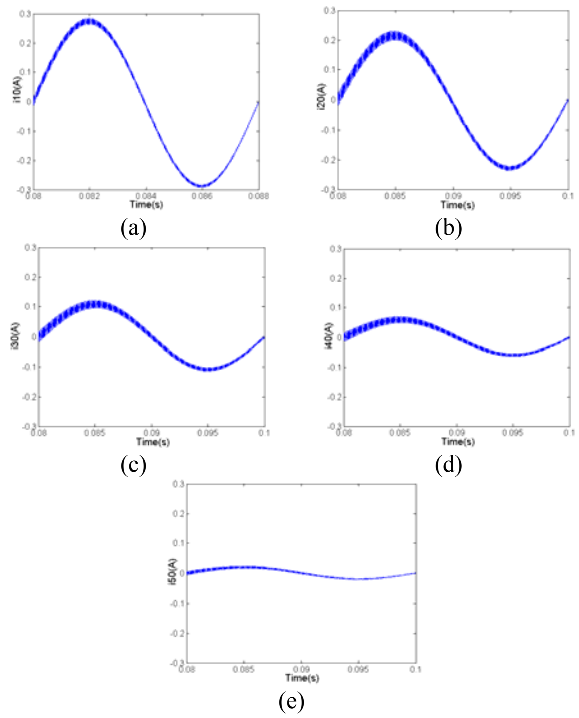

Fig.4. Power frequency zero sequence current

Table 2. Power frequency zero sequence current amplitude of every detection point

	*i*10	*i*20	*i*30	*i*40	*i*50
Amp	0.1988	0.1571	0.0772	0.0424	0.0142
Ratio	0.7902	0.4799	0.5492	0.3349	
Fault	No	No	No	Yes	

Table 3. Approximate entropies of every detection point

	*i*10	*i*20	*i*30	*i*40	*i*50
ApEn	0.2948	0.2808	0.5851	0.5666	0.6311
Ratio	0.9525	0.4799	0.9684	0.8978	
Fault	No	Yes	No	No	

D. *Approximate entropy based fault type recognition verification*

In the distribution network shown in Fig.2, a large number of single phase grounding faults, with fault angle 18º, 45º and 90º, respectively, and fault resistance 2Ω, 5Ω, 10Ω, 20Ω and 50Ω, respectively, are simulated in section *NO* and section *OP* of the feeder L_3. The transient zero sequence currents of the detection points *M*, *N*, *O*, *P* and *Q* are detected, and the corresponding approximate entropies are calculated. When the fault is located in section *NO*, the relation curves between the approximate entropies of upstream transient zero sequence currents and the corresponding fault angles are shown in Fig.5. When the fault is located in section *OP*, the relation curves between the approximate entropies of transient zero sequence currents and the corresponding fault angles are shown in Fig.6. From Fig.5 and Fig.6, we can see that when the fault resistance does not change and the fault angle changes, the approximate entropy does not change.

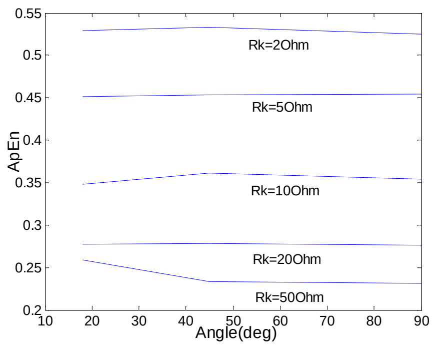

Fig.5. Relation curves between the approximate entropies and fault angles

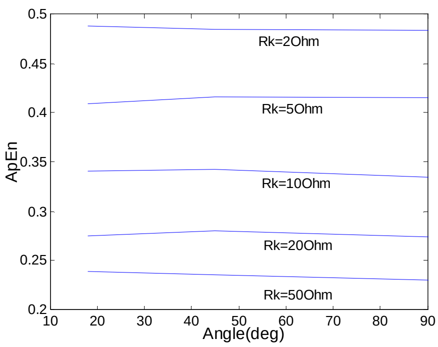

Fig.6. Relation curves between the approximate entropies and fault angles

When the fault is located in section *NO* and the fault angle is 18º, 45º and 90º, respectively, the relation curves between the approximate entropies of transient zero sequence current at point *N* and the fault resistances are shown in Fig.7. When the fault is located in section *OP* and the fault angle is 18º, 45º and 90º, respectively, the relation curves between the approximate entropies of transient zero sequence current at point *O* and the fault resistances are shown in Fig.8. From Fig.7 and Fig.8, we can see that the approximate entropy of transient zero sequence current changes with the fault resistance.

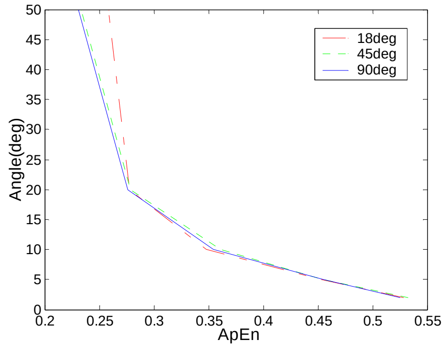

Fig.7. Relation curves between the approximate entropies and fault resistances

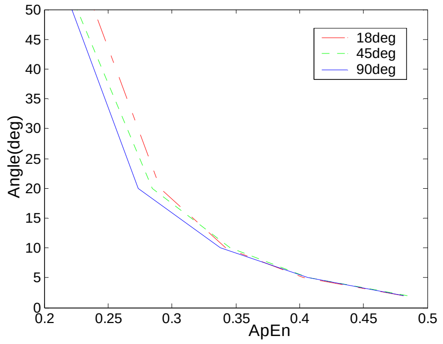

Fig.8. Relation curves between the approximate entropies and fault resistances

According to several sets of data of approximate entropy and fault resistance, the function between approximate entropy and fault resistance can be obtained using the interpolation method. The approximate entropy of actual transient zero sequence current at detection point is substituted into the corresponding function and the forecasting fault resistance is calculated. So the fault type is recognized.

For example, a single phase grounding fault occurs in section *OP*. When the fault angle is 45º and the fault resistance is 2Ω, 5Ω, 10Ω, 20Ω and 50Ω, respectively, the approximate entropy is calculated, respectively. Using three times spline interpolation, the function $R_k=f_p(ApEn(p))$ is approximated. The approximate curve is shown in Fig.9. When the fault angle is 90º and the fault resistance is 2Ω, 5Ω, 10Ω, 20Ω and 50Ω, respectively, the approximate entropy is calculated, respectively, and substituted into formula (6). The forecasting fault resistances and relative errors are shown in Table 4. From the table, we can see that the proposed method can forecast fault resistance accurately and recognize the fault type.

5. Conclusions

The study presents a fault localization method based on approximate entropy of transient zero sequence current. First, the structure of intelligent feeder automation is introduced. Each FTU detects the transient zero sequence current at the corresponding detection point and calculates its approximate entropy. The master station determines the fault localization and fault type. Second, the principle of fault localization and fault type recognition based on approximate entropy of transient zero sequence current is discussed in detail. According to the approximate entropies of the adjacent detection points, the fault localization can be realized. According to the function between approximate entropy and fault resistance, the fault type can be recognized. Third, to prove the proposed fault localization method, the EMTP/ATP based simulation is carried out for distribution network. The simulation results show that the proposed fault localization and fault recognition method is feasible and accurate. It can be used in smart distribution grid.

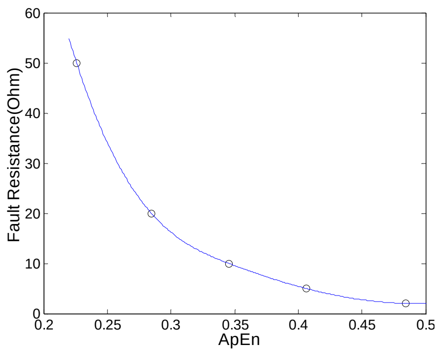

Fig.9. Approximate curve between approximate entropies and fault resistances

Table 4. Forecasting Fault Resistances

ApEn	Forecasting Fault Resistance(Ω)	Actual Fault Resistance(Ω)	Relative Error
0.4819	2.0214	2	1.07%
0.4064	4.9738	5	-0.52%
0.3376	10.7662	10	7.66%
0.2735	23.5733	20	17.87%
0.222	53.1513	50	6.3%

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