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Fault Detection in Complex Distribution Network Based on Hilbert-Huang Transform

Zhongjian Kang*, Aina Tian, Yanyan Feng
Department of the Electrical Engineering of China University of petroleum
Qingdao, China, 053286983450
*Corresponding author, e-mail: kangzjzh@163.com, tianaina2199@yahoo.cn, fengyy0116@yeah.net

Abstract

Traditional distribution network fault location methods often cannot be effectively applied for the structure of the branch in complex distribution network. A new accurate fault location for the single-phase-ground fault in complex distribution network with structure of the branch based on Hilbert-Huang transform was proposed in this paper. First, the distribution network was modeled. The faults on each branch were simulated. The energy characteristics under the branch in a particular frequency band were identified by HHT. Then these energy characteristics were used to train artificial neural networks (ANN).When the energy characteristics of actual fault are inputted, the trained neural network can output the malfunction branch. When the fault branch was determined, using the online fault feature matching method, combined with the genetic algorithm, the precise determination of the distance to fault location in the fault branch can be completed. With combinations of signal processing-Hilbert-Huang transform, artificial neural network and genetic algorithm, the entirely new method was proposed to deal with the problem of fault location in distribution network in this article. The results showed that the method has a good precision and apply to the small current grounding system.

Keywords: *Complex Distribution Network, Hilbert-huang Transform (HHT), Energy Characteristic, Artificial Neural Network*

1. Introduction

Distribution network fault location has always been one of the most important research issues in power system. With many branches, complex structure, large grounding resistance and other reasons in distribution network, it makes the distribution network fault location become a problem. Most distribution networks are small current grounding system in China, and fault characteristics are small. Actual fault location still relies on manual line patrol. The workload is huge. Usually, the measuring device installed only at the first end of the feeder in the general distribution system.However, it is unrealistic to install measuring device at each branch point. Branch point has attenuation and distortion effect on transient signal. When the measuring of the damped transient signal is quite weak, it cannot detecte the fault signal or produce false failure points. Thus no method can complete accurate fault positioning. There have been several existing traditional fault-location methods. According to the principle, they can be divided into impedance method, traveling wave method, the injection method and fault detector method [1-10]. However, these traditional methods are not good solutions to distinguish the pseudo-point of failure in the distribution network with branches. In recent years, domestic and international distribution network fault location techniques are improved based on the several traditional positioning methods. But there is no fundamental breakthrough. And some fault-location methods are feasible in theory. However, there are more or less problems in practical application. The results are not ideal. Considering the advantages and disadvantages of the current distribution network fault-location methods and the existing problems, a determination method that can find out fault branch in distribution network based on Hilbert-Huang transform is proposed to solve for the problem of many branches. Combined with artificial neural network, this method can effectively find the actual fault branch to exclude the pseudo-point of failure, so that the distance measurement accuracy is improved.

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2. Distribution Network Single Phase Grounded Fault Analysis

When there is a fault in distribution network where the neutral point grounded by the arc suppression coil, the branch of the normal operation can be equal to a serial and parallel LRC branch, no matter in which branch did the point of failure occur. The equivalent circuit is shown in Figure 1. With the equivalent circuit in Figure 1, the fault transient process can be analyzed. And the transient characteristics of the fault ground current can be examined.

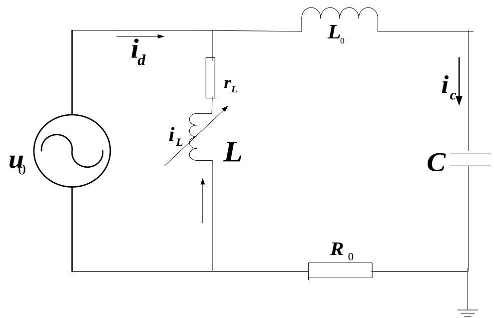

Figure 1. Transient Current Equivalent Circuit of Arc Suppression Coil Grounded Distribution Network with Single Phase Grounded Fault

2.1. Single-Phase-Ground Fault Transient Capacitive Current

Due to the arc suppression coil inductance L ? L_0 and the free oscillations frequency of capacitance current are very high, r_L and L can be ignored in the equivalent circuit diagram. In such case, the equivalent circuit is only equivalent to that a zero-sequence sinusoidal voltage $u_0(t) = U_m \sin(\omega t + \varphi)$ is suddenly applied to the series circuit composed of R_0, L_0, C, then:

$$R_0 i_C + L_0 \frac{di_C}{dt} + \frac{1}{C}\int_0^i i_c dt = U_m \sin(\omega t + \varphi) \quad (1)$$

The transient capacitive current i_C can be divided into two parts. One is transient natural vibration component i'_C. And the other is Steady-state power frequency component i''_C. When $t = 0$, $i'_C + i''_C = 0$. Considering $I_{Cm} = U_m \omega C$,by Laplace transform, the transient expression of the capacitor current is given:

$$i_C = i'_C + i''_C = I_{Cm}[(\frac{\omega_f}{\omega}\sin\phi \sin\omega t - \cos\phi\cos\omega_f t)e^{-\delta t} + \cos(\omega t + \phi)] \quad (2)$$

There, U_m is phase voltage amplitude, I_{Cm} is capacitive current amplitude, ω_f is transient component angular frequency of free oscillations, δ is attenuation coefficient for the free-oscillation component， $\delta = \frac{1}{\delta_C} = \frac{R}{2L_0}$， τ_C is time constant of the loop.

If single-phase-ground fault occurs on different branches, then the calculated equivalent capacitance C of the Figure 1 is different. Therefore, when the fault occurs on different branches, the corresponding time constant τ_C varies. The attenuation speed of free oscillation is determined by τ_C .Therefore, the faults on different branches have different transient characteristics. In the medium and low voltage power grid, the natural vibration frequency of transient capacitive current is usually in the range of 300Hz- 3000Hz [11].

2.2. Single Phase Ground Fault Transient Inductor Current

The constraint equation of the arc suppression coil in the equivalent circuit is given:

$$U_m \sin(\omega t + \phi) = r_L i_L + W \frac{d\psi_L}{dt} \tag{3}$$

Where ψ_L is the magnetic flux value of the arc suppression coil core, W is the tap coil turns of the arc suppression coil.

The expression of the magnetic flux ψ_L is as:

$$\psi_L = \psi_L' \frac{\omega L}{Z}[\cos(\phi + \xi)e^{\sqrt{\frac{t}{\tau_L}}} - \cos(\omega t + \phi + \xi)] \tag{4}$$

Considering $r_L << \omega L$, so $Z \approx \omega L$, $\xi = 0$,then transient inductor current is expressed as:

$$i_L = I_{Lm}[\cos\phi e^{-\frac{t}{\tau_L}} - \cos(\omega t + \phi)] \tag{5}$$

The oscillation angular frequency of transient current is the same as the frequency of power supply. The amplitude of the transient current largely depends on the phase angle value of the fault phase voltage. If fault occurs on the time when phase angle is 0, then the transient DC component is the largest and the decay rate is fastest that attenuation can be finished within a power frequency cycle. If fault occurs on the time when phase angle $\varphi = \pi/2$, then the transient DC component is the smallest. The decay rate is slower so that the attenuation process can last for 2to5 cycle time [12].

2.3. The Characteristic Energy of Single-Phase-Ground Fault Transient Ground Current

Transient ground current is composed of transient inductor current and transient capacitive current, its expression is shown as:

$$i_d = i_C + i_L = (I_{Cm} - I_{Lm})\cos(\omega t + \phi) + I_{Cm} \times [\frac{\omega_f}{\omega}\sin\phi \sin\omega t - \cos\phi \cos\omega_f t]e^{-\frac{t}{\tau_C}} + I_{Lm}\cos\phi e^{-\frac{t}{\tau_C}} \tag{6}$$

HHT can be used to extract the characteristic energy of the current and analyze them. Assuming that the point a and point b. They are the same topology, a point equal to the distance from the head-end. When the load of the two lines are same and different, the characteristic energy of the single-phase ground fault currents are shown as Figure 2.

From Figure 2, it is can be seen that the characteristic energy of the fault current is significantly different with different loads. Generally speaking, the load different branch carried will not be exactly the same. So the fault points in different branches are the same distance away from the head end. They can also be distinguished by failure characteristics.

Assuming c, d two points, they are 6km away from the head end with the same load. In the topology structure, two points for the head end are not equivalent. The characteristic energy of the single-phase ground fault current is shown in Figure 3.

It can be seen from Figure 3, when a fault occurs in points that are equal distance away from the head end and with the same load, due to the different location in the network topology, the characteristic energy is different.

Assuming c, e, f three points, they are in the same branch. The characteristic energy of the single-phase ground fault current is shown in Figure 4.

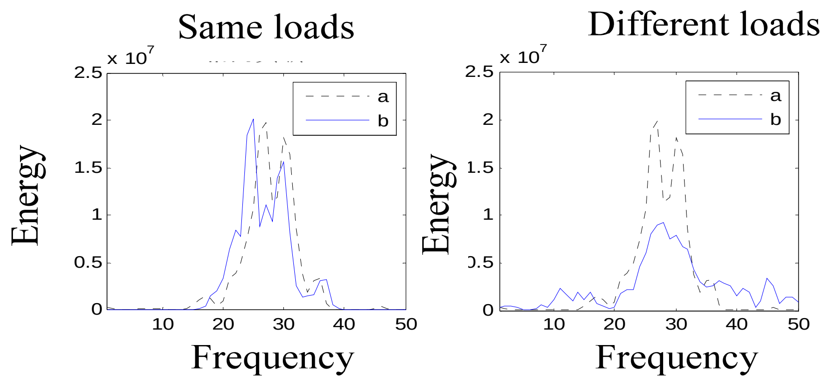

Figure 2. Fault Characteristic Energy of AG Fault at a and b with the same and different Loads

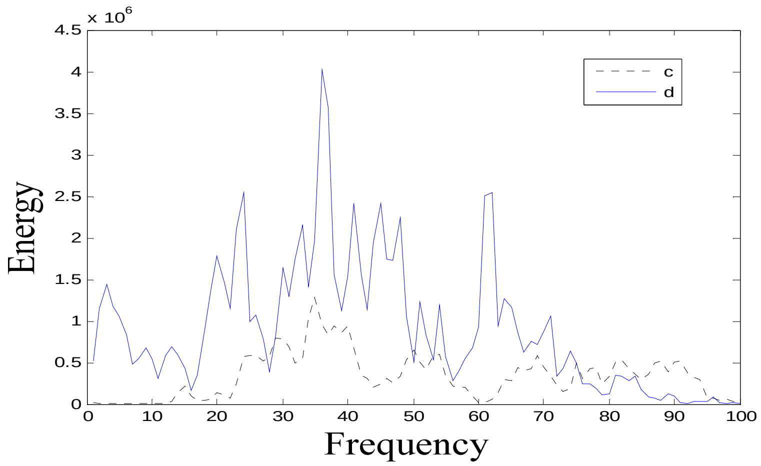

Figure 3. Characteristic Energy of AG Fault at c and d

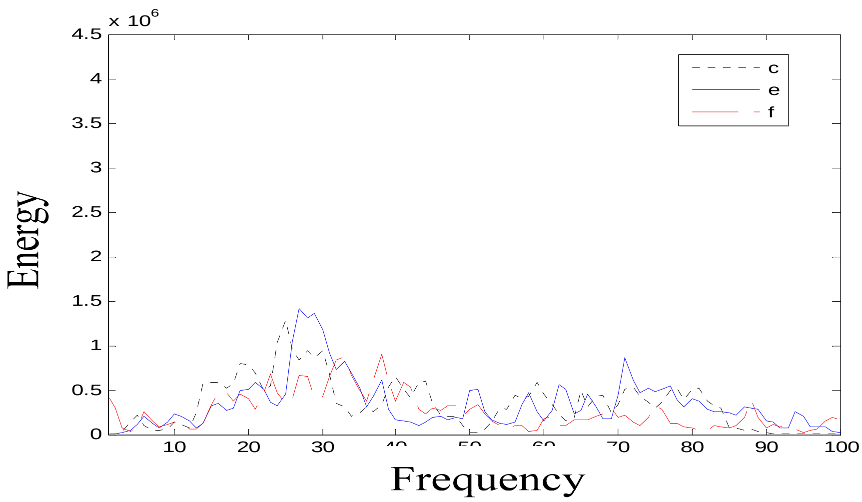

Figure 4. Characteristic Energy of AG Fault at c、e and f

It can be seen from Figure 4 that although their distance from the head end is different, the characteristic energy is similar because the three points are in the same branch. When fault occurs in different points of the same branch, they are similar on the characteristic energy, which can be used as a basis to select fault branch.

3. Study On Single-Phase Ground Fault Location In Complex Distribution Network Based On Hilbert-Huang Transform

3.1. Method to Determine Fault Branch in Complex Distribution Network Based on Hilbert-Huang Transform and Neural Network

The neural network has a strong learning, adaptive ability and a good nonlinear mapping ability. It can approximate any complex nonlinear relationship [13]. With neural network applied to established HHT module, the fault zero sequence voltage and zero sequence current are processed. Then the fault transient energy can be got. After that, these zero-sequence voltage and zero-sequence current values are used for HHT analysis to get time-frequency-energy joint distribution. Finally, the energy values are taken as neural network training samples.

There are six branches, so the output layer neuron number is set on six. The output is encoded as follows:

```
1 0 0 0 0 0 , correspond 1# branch;
0 1 0 0 0 0,  correspond 2# branch;
0 0 1 0 0 0,  correspond 3# branch;
0 0 0 1 0 0,  correspond 4# branch;
0 0 0 0 1 0,  correspond 5# branch;
0 0 0 0 0 1,  correspond 6# branch;
```

The input matrix of the neural network $ANNin$ is a matrix whose dimensional is 100×300. Each column corresponds to a sequence of the energy value. The sequence of the energy value is the transient characteristics in frequency range 3kHz-9kHz. The training sample number is 300.

The artificial neural network is evaluated in computing time, the efficiency of the algorithm, topology complexity and so on. In terms of the theoretical analysis, BP artificial neural network has a rigorous theoretical system. However, the learning time of BP artificial neural network is long. The Convergence rate is slow. When the number of hidden layer neurons is increased, the training correct rate improved significantly. But the training time becomes longer. When the number of neurons is too small, it is likely to lead to a failure train.

There is no rigorous theory show us how to choose the number of the BP neural network hidden layer and the number of hidden layer neuron. The choice is all depended on virtue of experience or experiment. “The more the number of the neural number, the better” is not suitable to practical problems. The performance of the Network is better when the number of the hidden layer neuron is increased. But, the cost is larger amount of computation and longer computing time. At the same time, when the number of the hidden layer neuron is not enough, it is difficult to meet the training objectives and requirements.

The number of the input neurons is set to one hundred. The number of the output neurons is set to six. The number of the training sample is three hundred. The training objectives accuracy is set to 10^{-4}.The number of the layer is set to one. The number of the layer neural is set to twenty. All the settings are based on the experiments. The neural network training process for fault branch selection is shown in Figure 5.

3.2. Research on Fault Location in Complex Distribution Network with Single Phase Grounded Fault Based on Genetic Algorithm

Genetic Algorithm (GA) is an optimization algorithm that simulates the Darwin's theory of biological evolution. By simulating natural selection and biological evolution, GA find the global optimum.

The basic operation of GA is as follows:

First. Initialization: Count evolution Generation $i=0$, set the Maximum evolution generation and randomly generated initial population P_0 whose quantity is N.

Second. Individual evaluation: calculate each individual's fitness in the i-th generation population P_i .

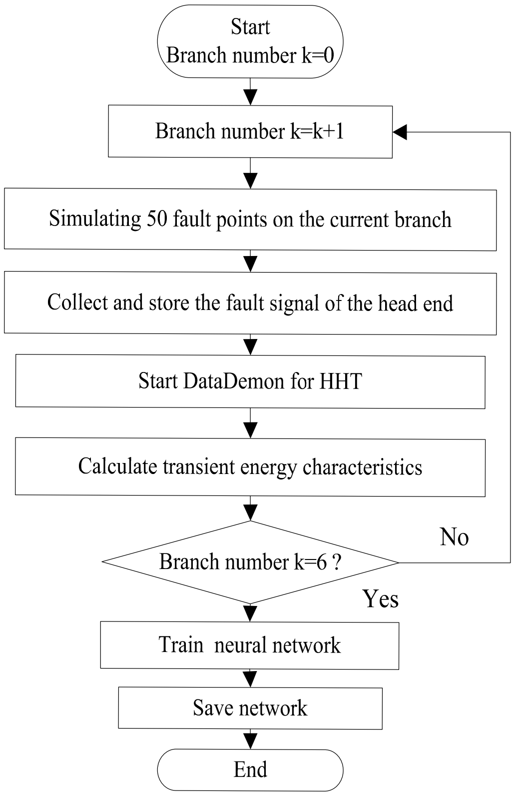

Figure 5. Training Flowchart of Neural network for Branch Selection

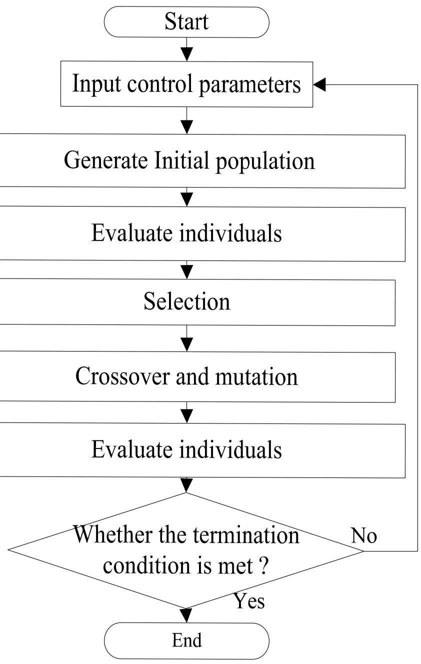

Figure 6. The flowchart of Genetic Algorithms

Third. Selection: choose individuals with good fitness from the parent population and eliminate the bad individuals. In this way, the excellent genes are inherited by next generation. The commonly used selection methods are the roulette method, twenty-two competition law, ranking selection method and so on.

Fourth. Crossover operation: exchange or combine several particular genes on the chromosomal gene of the two individuals, generate a new offspring individual. The crossover operator is the most unique part and also plays a central role in the genetic algorithm.

Fifth. Mutation operation: change the value of certain genes of some individual groups. The i-th generation population P_i must go through the selection, crossover and mutation process, to produce its next-generation populations P_{i+1} .

Sixth. Termination condition: if $i = T$ when the generation reaches the set maximum evolution generation, the individual whose fitness is the biggest is outputted. This individual is the optimal solution.

The flowchart of Genetic Algorithms is as Figure 6. The basic idea of GA is started from an initialized groups. After random selection (copy), crossover and mutation genetic manipulation, the most viability chromosome survives with maximum possibility. So groups evolve to getting better search space area from generation to generation [14].

When single-phase ground fault occurs in distribution network, fault branch is first selected, then GA is used for fault matching on fault branch. Fault distance, fault time, grounding resistance has a decisive role in the failure characteristics. Fault distance, failure moment, grounding resistance are set as variables. Fault feature matching process is to find out the fault point whose difference between simulation characteristic energy and practical features energy is minimum. This simulation fault point is the actual fault point. The fault distance of this simulation fault point is the actual fault location. Fault location process of complicated distribution network with branches is shown in Figure 7.

In Figure 7, the genetic algorithm matching is a sub-process. The specific approach is illustrated as follows. The N faults are simulated in each selected fault branch. The ground fault distance and fault resistance of each simulation are changed. N fault energies are obtained. These fault energy obtained is compared with the actual fault energy. The point with the smallest difference is taken as the fault point. The match is successful. The flowchart of Fault-match Method based on GA is shown in Figure 8.

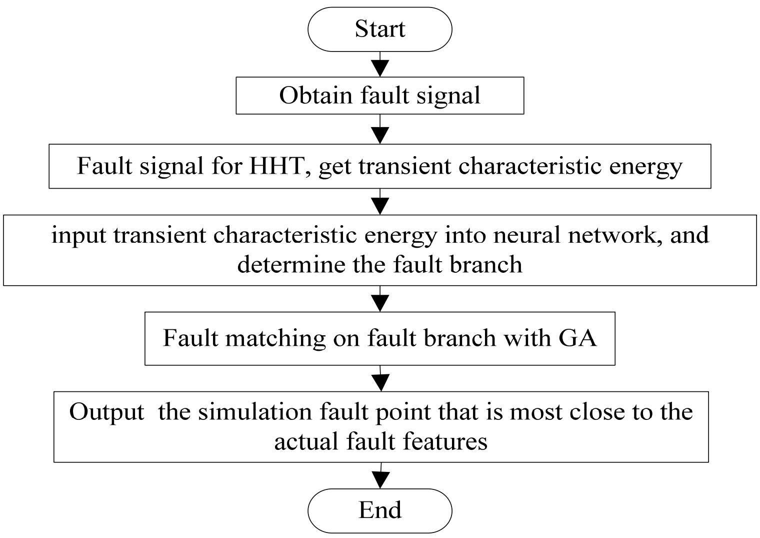

Figure 7. The flowchart of Fault Location in Distribution network with Branches

In genetic algorithm, the basis of investigating individual fitness is the fitness function. In this paper, the non-power frequency transient energy in high frequency [13] is used to build the fitness function. The first step is to get the zero sequence voltage and zero sequence current of the actual fault point measured at the head end. The second step is to calculate the non-power frequency transient energy in high frequency.

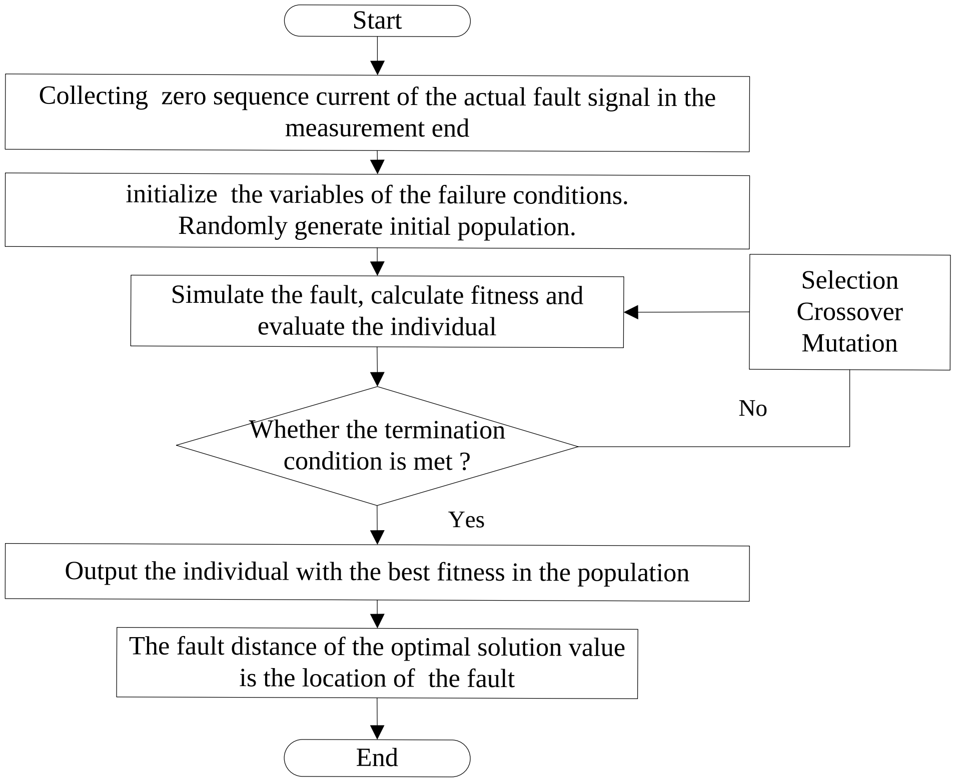

Figure 8. The flowchart of Fault-match Method based on GA

Compared with the simulated non-power frequency transient energy in high frequency in various fault conditions. The third step is to build fitness function using the differences between them. The expression of fitness function is given:

$$Fit = \frac{1}{1 + \left| W_{real} - W_i \right|} \tag{9}$$

Where, W_{real} is the non-power frequency transient energy in high frequency of the actual fault measured at the head end. W_i is the non-power frequency transient energy in high-frequency that is measured at the i-th simulation of distribution network model , corresponding to in the i-th individual in the genetic algorithm. The solution that makes fitness function value biggest is the optimal solution.

4. Simulation and Analysis

The established simulation model in distribution network is simplified as Figure 9. Due to medium voltage distribution network is primarily a small current grounding system in China, so the built distribution network model is grounded by the arc suppression coil to ensure its representativeness. The branch line length is set as follows: No. 1branch 10 km, number 2-6 branch 5km. Three-phase transmission circuit model adopt distributed parameter model. The line of unit length parameter is set to: positive sequence and zero sequence resistance are

0.17Ω and 0.23Ω, positive sequence and zero sequence inductance are 1.2mH and 5.48mH, positive sequence capacitance and zero sequence capacitance are 9.697nF and 6nF.

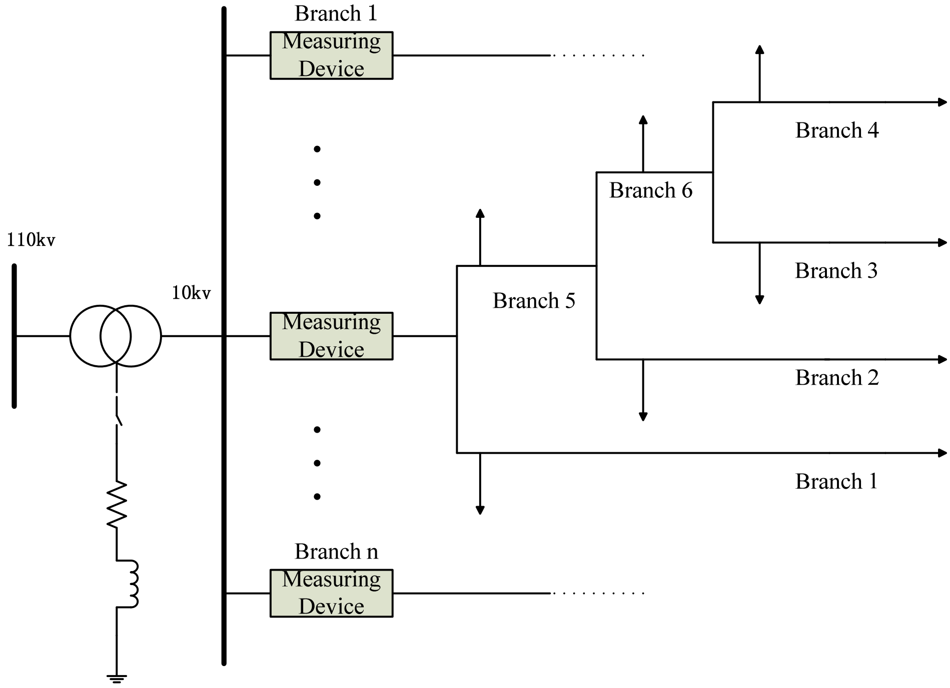

Figure 9. Equivalent circuit diagram of simulation model

4.1. Simulation and Analysis of Fault Branch Determination

The load of Branch 1, 2, 3, 4 carried is respectively 8000kW, 5000kW, 1500kW and 1500kW. Including the branches, 5, 6, 50 points simulating single phase-to-ground fault in each branch at equal intervals are taken. Then 300 training samples are generated. These samples are used to train artificial neural network to determine fault branch. After that, the original training data is used to verify the correctness of the network, and the accuracy of branch determination can reach 100%. Randomly generating fault point in every branch is used to test the correctness of the network. The results are shown as Table 1.

Table 1. Result of the Fault Branch Detection

Actual fault branch	Fault distance /km	Fault branch detection	Correct or not
1	2.50	1	correct
	5.00	1	correct
	7.50	1	correct
2	0.90	2	correct
	1.80	2	correct
	2.70	2	correct
3	0.85	3	correct
	1.70	3	correct
	2.55	3	correct
4	1.00	4	correct
	2.00	4	correct
	3.00	4	correct
5	0.95	5	correct
	1.90	5	correct
	2.85	5	correct
6	0.80	6	correct
	1.60	6	correct
	2.40	6	correct
Correct rate		100%	

It can be seen from Table 1, the method can all correctly distinguish the fault branch in the total 18 fault points. The correct rate reaches 100%. It verifies the correctness of the method that determines the fault branch using neural network proposed in this paper.

4.2. Simulation and Analysis of Fault Location Matching

Distribution network model grounded by arc suppression coil based on figure 8 is established. First 4 fault points are respectively set in the six branches. Then the zero-sequence voltage and zero-sequence current of the head end are obtained, finally the fault characteristic energy is got by using HHT. The fault conditions are matched (fault distance and the ground resistance) with the genetic algorithm. The experimental results is shown in Table 2. The relative error in the table refers to the percentage of the absolute error attributable to the total length of the distribution network.

Table 2. Result of the Fault Location Matching

Branch	Fault condition		result	Error	
	Ground resistance/ Ω	Fault distance /km	L/km	Absolute /km	Relative/%
1	1	2.00	2.17	+0.17	0.48%
		7.00	7.11	-0.11	0.31%
	100	2.00	1.80	-0.2	0.57%
		7.00	6.60	-0.40	1.14%
2	5	0.50	0.62	+0.12	0.34%
		2.00	2.00	0	0
	50	0.50	0.69	+0.19	0.54%
		2.00	2.13	+0.13	0.37%
3	0.5	0.50	0.59	+0.09	0.26%
		3.00	3.00	0	0
	100	0.50	0.35	-0.15	0.43%
		3.00	3.24	+0.24	0.68%
4	5	1.00	0.97	-0.03	0.09%
		3.50	3.45	-0.05	0.14%
	100	1.00	0.88	-0.12	0.34%
		3.50	3.66	+0.16	0.46%
5	0.1	1.00	1.02	+0.02	0.06%
		2.50	2.48	-0.02	0.06%
	50	1.00	1.08	+0.08	0.23%
		2.50	2.60	-0.10	0.29%
6	25	0.30	0.30	0	0
		3.00	3.00	0	0
	200	0.30	0.51	+0.21	0.60%
		3.00	2.80	-0.20	0.57%

It can be seen from Table 2, when the ground fault resistor is small, the result is preferable. The absolute error is within 300m. When the fault grounding resistance is larger, the result is worse than the former.

The fault-matching technique based on genetic algorithm need higher requirements for initial population. If some individual is similar to the actual fault condition in the initial population, it is the better to locate the fault location. With comprehensively view of all six branches of the 24 fault points, all basically meet the error requirements for fault location. The result of the fault location method based on genetic algorithms and fault characteristics match is good.

5. Conclusion

This paper proposes a new distribution network fault branch identification method based on HHT. The simulation results show that this method has higher fault location accuracy. This article obtains the following main conclusions:

First, the branches in the distribution network is an important reason why distribution network fault location is more difficult than transmission line fault location.

Second, the method using rich transient fault information contained in the early fault time for fault location, can effectively overcome the shortcomings that the small current grounding system fault current is small and the fault detected is hard. This method is suitable for distribution network fault location of the small current grounding system.

Third, this distribution network fault branch selection method based on HHT has better resolution. The method applies HHT analysis and extractes transient characteristics of fault zero sequence voltage and zero sequence current.

Forth, the new signal processing method-HHTcombined with artificial neural network and genetic algorithm makes fault branch determination and accurate fault location more effectively.

Fifth, this method just need to get the fault signal of the head. It can determine fault branch on downstream fault branch and fault location, which is suitable for most of the distribution network in China at present, and has a good economy.

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References

[1] Rodrigo Hartstein Salim, Mariana Resener, André Darós Filomena. Extended Fault-Location Formulation for Power Distribution Systems. *IEEE Transactions On Power Delivery*. 2009; 24(2).
[2] MaShicong. Fault Location Techniques for Non-effectively Earthed System Based on Transient Signals, PhD Thesis. ShanDong University; 2008.
[3] Wang Jinqiang, Xi Simin, Yin Yanhe. Optimized Matrix Algorithm for Fault Section Detection in Distribution Network, *Electrotechnics Electric*. 2010; 12: 12-70.
[4] Guo Zhuangzhi, Wu Jiekang,. Electromagnetism-like Mechanism Based Fault Section Diagnosis for Distribution Network, *Proceedings of the CSEE*. 2010; 30(13): 34-40.
[5] Zhou Qiangfu, Qu Lili, Li Bingyin, Wu Mao. Development of An Automatic Faults Location System Based on Faults Indicator for Distribution Lines. *Southern Power System Technolog*y- *Study & Analysis*. 2010; 4(5).
[6] Hongsheng Su, Yunchuan Zhang. Distribution Grid Fault Location Applying Transient Zero-mode Current. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(5): 883-890.
[7] Zhai Yunjuan. Study of Automatic Fault Location Techniques for Distribution System Based on Signal Injection Method. PhD Thesis. ShanDong University; 2009.
[8] Xu Rujun,YanFeng,Pei Yulong. Research on the Location Method of Single Phase Grounding Fault for 10kV Distribution Line. J*ournal of Electric Power Science and Engineering*. 2010; 26(11): 14-17.
[9] Hou Zili, Peng Lanfang. Port-Fault Diagnosis:The Principle and Algorithm. J*ournal of Beijing University of Posts and Telecommunications*. 1990; 13(2): 66-72.
[10] Yang Xuechang, Weng Yangbo, Wu Zhensheng. Theoretical Analysis of Transfer Function Algorithm for Grounded Fault Location in Three Phase Power Distribution Lines. J*ournal of High Voltage Apparatus*. 2002; 38(12): 15-18.
[11] Yuan Ye. Research on Single-Phase to Ground Fault Selection Technology in Distribution Networks Based on Transient Component. PhD Thesis. Yanshan University; 2009.
[12] Shu Hongchun. A Fault Line Detection Algorithm for Distribution Network. *Beijing Machinery Industry Press;* 2008.
[13] Patricia Melin, Victor Herrera, Danniela Romero, Fevrier Valdez, Oscar Castillo. Genetic Optimization of Neural Networks for Person Recognition Based on the Iris. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(2): 309-320.
[14] Lei Yingjie, Zhang Shanwen, Li Shuwu. MATLAB Genetic Algorithm Toolbox and its Application. Xi'an University of Electronic Science and Technology; 2005.
[15] Gao Lei, “Research on the Application of HHT Theory to Power System”, Northeast Dianli University; 2006.