International Journal of Grid and Distributed Computing
Vol. 10, No. 1 (2017), pp.137-148
http://dx.doi.org/10.14257/ijgdc.2017.10.1.13

Study on Fault Line Selection for Single Phase Grounding in Distribution Network Based on Harmonic Wavelet Packet Energy Entropy

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Abstract

The transient zero-sequence current is decomposed by using harmonic wavelet packet transform in an isolated neutral system when Phase-to-ground fault occurred. The energy entropy of various scales is calculated. Because of every line's energy distribution is not always the same, the method of energy entropy utility value is present. The highest energy entropy utility value of band is selected as a feature frequency band, in each band. The selection of fault line is compared with polarity and magnitude of harmonic wavelet packet in feature frequency band. The result of simulation shows that the line selection method is correct.

Keywords: *Harmonic wavelet packet; energy entropy; fault line selection; feature frequency band*

1. Introduction

The small current grounding is a remarkable feature of distribution network in China. Neutral point non-grounding system and neutral point grounding through arc-suppression coil system are applied widely. When a single-phase grounding fault occurs in the small current grounding system, the current (capacitive current), which flows through the point of fault is smaller than the direct grounding current (single phase short circuit current). There are two main types of methods to select a fault line, steady signal method and transient signal method. The later [1] has higher sensitivity. Line selection method based on single band, is not reliable. Because, the frequency of transient current is affected by network parameters, fault time and another factors. The method based on multiple bands [2,3] using wavelet packet decomposition the fault transient zero sequence current. The energy of different frequencies bands was calculated. According to the largest energy principle and the principle that transient capacitive current has different amplitude and polarity between sound and fault phases to select the fault line. Different methods to select a feature frequency band or a combined feature frequency band were put forward In [4,5]. Although signal decomposition based on wavelet packet method overcomes the drawback of high frequency analysis, yet, increases the computational complexity and has the problem of spectrum aliasing.

This paper adopts harmonic wavelet packet method to solve the above problem. Among the sub-bands, which got by using harmonic wavelet packet to decompose the transient current signal. Did not exist the phenomenon of spectrum aliasing and energy

ISSN: 2005-4262 IJGDC

leakage. Signal of sub-bands can accurately describe the time-frequency characteristics and energy distribution of original signal. Meanwhile can get the same resolution results in arbitrary decomposed layers. [6-8] Wavelet Entropy based on the wavelet transform [9,10] could describe time-frequency characteristics of signals by calculation. Combination the advantages of harmonic wavelet packet and wavelet entropy. Decompose the transient zero sequence current signal by harmonic wavelet packet when fault occurred. Extraction and reflects the characteristics of single-phase grounding fault. Calculation harmonic wavelet packet entropy of each sub-band. The feature frequency band is selected adaptively. Then compare harmonic wavelet packet coefficients in the feature frequency band.

2. Basic Principle of Harmonic Wavelet

Newland who worked in cambridge university, put forward a clear expression complex wavelet with the box-like spectrum, in 1993. Harmonic wavelet is very sensitive to the amplitude changes of vibration signal and has good filtering characteristics, which can extract the weak signal effectively. Harmonic wavelet can carry on the accurate time-frequency decomposition to the signal and have fast calculating and high precision characteristics. [11-13] Expression in frequency domain as:

$$\psi_{m,n} = \begin{cases} \dfrac{1}{2\pi(\mathrm{n-m})} & (2\pi n \le \omega \le 2\pi m) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Where, m,n are scale parameters, ω is the frequency of distribution network. Conduct fourier transformation on formula(1), get the expression in time domain as:

$$\omega_{m,n}(t) = \frac{e^{j2\pi nt} - e^{j2\pi mt}}{j2\pi(n-m)t} \quad (2)$$

Where, $\psi_{m,n}(t)$ is the Wavelet coefficients after decomposition, $j^2 = -1, t$ is time.

Assuming harmonic wavelet displacement as $k/(n-m), k \in Z$, and the equation (2) can be expressed as [14]:

$$\psi_{m,n}(t - \frac{k}{n-m}) = \frac{e^{jn2\pi(t-\frac{k}{n-m})} - e^{jm2\pi(t-\frac{k}{n-m})}}{j2\pi(n-m)(t-\dfrac{k}{n-m})} \quad (3)$$

This is the the general expression of harmonic wavelet with the band width is $2\pi(n-m)$,and the analysis center is at $k/(n-m)$.

It can be seen that in the circumstances of different spectrum. There are non-overlapping frequency bands.Wavelets are always orthogonal to each other and that wavelets in the same frequency band are orthogonal when k is any non-zero integer [15].

According to the expression of harmonic wavelet in time domain, harmonic wavelet decomposition level was determined by scale parameter m,n. Similar to other wavelet decompose method. The decomposed signal has better resolution in low frequency. High frequency's resolution is not better, when the number of decomposed layer is increasing. To get better resolution in high frequency band, Dyadic harmonic wavelet packet transform was used to decompose original signal [16]. Scale parameters m, n need to satisfy the formula (4) to get a needed decomposition accuracy in the whole frequency band:

$$\begin{cases} m = if_b, n = (i+1) f_b & (i = 0,1,\cdots,2^s - 1) \\ f_b = f_h / 2^s & (i = 0,1,\cdots,2^s - 1) \end{cases} \quad (4)$$

Where, s is the number harmonic wavelet packet decompose layer, f_h is the highest analysis frequency, f_b is analysis bandwidth. By formula (4) , we can obtain the frequency distribution of harmonic wavelet, see as Figure 1.

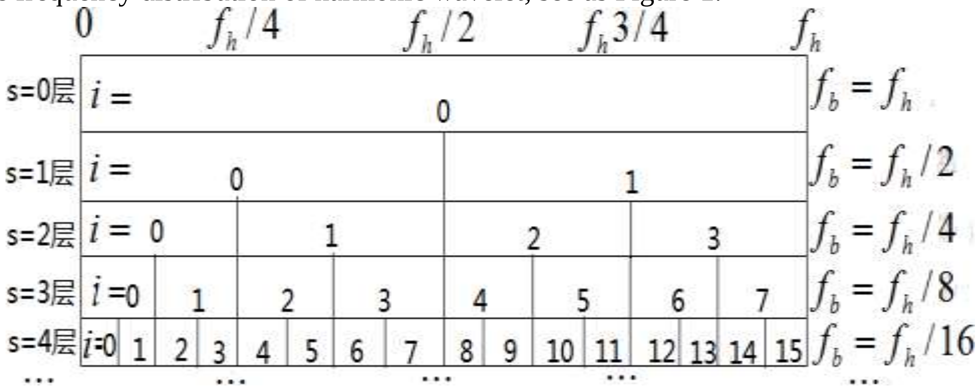

Figure 1.The Frequency Distribution of Harmonic Wavelet Packet

The specific steps of harmonic wavelet packet decomposition were summarized as follows:

First, do Fourier transformed, with N sampling points about signal in the time domain.

Second, according to the analysis of the highest frequency and wavelet decomposition layers partition the nodes.

Third, making the inner-product with harmonic wavelet, in the frequency domain.

Fourth, making inverse Fourier transform of inner-product operation result.

Through these steps, wavelet coefficient in each harmonic wavelet packet node can be obtained.

3 Entropy Theory

3.1. Information Entropy

Clausius, who uses thermodynamic entropy to metric the ability of transforming heat to power, is the first to introduce entropy to thermodynamics. Further, Shannon put forward information entropy to measurement randomness size of discrete random variable.

For an uncertain system, considering a random event X which has n possible results. The size of randomness can describe by probability distribution function. A possible probability distribution is $p = (p_1, p_1, \cdots p_n)$, which satisfies the condition:

$$0 \le p_l \le 1 \quad (l = 1,2,\cdots,n), \ \sum_{l=1}^{n} p_l = 1$$

The information entropy (Shannon entropy) is:

$$H(X) = -\sum_{l=1}^{n} p_l \log p_l \quad (5)$$

Where, n is the number of possible results, p_l is The possibility of even l.

Entropy is a macro-characteristic of a system. Total entropy of a system equals the sum of every part's entropy in the system. It assumes that the system is composed of m sub-systems, the total entropy of the system S is as follows [20]:

$$S = \sum_{l=1}^{m} S_l = \sum_{l=1}^{m} k \ln p_l + C \quad (6)$$

Where, m is the number of sub-system, S_l is the entropy of sub-system l, k is a coefficient of the system and C represents a constant.

3.2. Wavelet Energy Entropy

Wavelet energy entropy combine wavelet transform and information entropy.

According to the characteristic of orthogonal wavelet, the total energy of a signal in a time window was equal to the sum of every part's energy. The formula is:

$$E = \sum_j E_j \quad (7)$$

$$E_j = \sum_k \left| D_j(k) \right|^2 \quad (8)$$

Where, E is a signal's whole energy, E_j is the energy of wavelet decomposition scale j, $D_j(k)$ is the wavelet coefficients under scale j.

The formula of wavelet energy entropy is as below:

$$W_{EE} = -\sum_j p_j \log p_j \qquad j = 1,2,...,m \quad (9)$$

In this formula, $p_j = E_j / E$, $\sum_j p_j = 1$.

Energy entropy can reflect the information of current distribution in the frequency domain. Spectrum can indicate the frequency distribution. Using harmonic wavelet packet to decompose the transient zero sequence current and calculate harmonic wavelet packet energy entropy in every scale. By this we can obtain the energy distribution for fault current. For the signal analyzed, the narrower and lower spectral peak in it's spectrum the lower complexity it has. It is correct in the contrary situation for transient current. It is favorable to select a fault line, which energy spectrum has high complexity. Based on these, choose the frequency band, which has the highest harmonic wavelet packet energy entropy, as the feature frequency band.

3. Fault Line Selection based on Harmonic Wavelet Packet Energy Entropy

3.1. Decompose Transient Zero Sequence Current Signal by Harmonic Wavelet Packet

The $x(m)$, $m = 0,1,..., N-1$ represents transient zero sequence current signal, N is the number of sampling point. Make Fourier transformation to $x(m)$, The data sequence is $X(0), X(1), X(2),\cdots, X(N-1)$.

According to harmonic wavelet packet decompose theory can get decomposition coefficients in different decomposition scales.

$$A_i = IFFT(X((i-1)N_v+1), X((i-1)N_v+2),\cdots, X((i-1)N_v+iN_v)) \quad (10)$$

Where $N_v = N/2^{(s+1)}$ is the number of decomposition coefficients, $s = 1,2,\cdots,n$ is the number of decomposition layers $i = (1,2,\cdots,2^s)$ is the number of decomposition scales, $IFFT$ represent for inverse Fourier transform.

3.2. Calculate Energy Entropy in Every Decomposition Scales

Like formula (9) Expression of harmonic wavelet packet energy entropy is as follows:

$$p_i(j) = A_i(j)/E \quad (11)$$

Where, $p_i(j)$ is the energy probability of serial number j in scale i . $A_i(j)$ is the decomposition coefficients of serial number j in scale i :

$$W_i = -\sum_{j=(i-1)N+1}^{iN_v} p_i(j)\log p_i(j) \quad (12)$$

Where, j is the serial number of decomposition coefficients, W_i is the harmonic wavelet packet energy entropy of scale i .

3.3. Method of Selection a Feature Frequency Band

For the selection of feature frequency band, if select a fixed band as the feature frequency band directly, Energy in different fault conditions all lines' entropy in this band is not always the biggest at the same time. It is easy to make mistakes in the line selection. The feature frequency bands should be selected based on the specific energy distribution situation and have larger entropy in every line's spectrum. The information of multiple lines can be used comprehensively.

Due to the complexity of the transient process, the lines transient frequency components and magnitude is different. Leading to the greatest energy entropy band is not always the same. For a situation, which does not have the same maximum entropy energy bands. Define an utility function, which aims to select the band that lines are all have larger entropy energy. To avoid getting a wrong result that caused by energy entropy value is too small. Expression of utility function is as follow:

$$X_m = \frac{1}{\left|\log(\frac{A_m}{A_{sum}})\right|} \quad (13)$$

$$A_m = \left|\log\prod_t^n W_{tm}\right| \quad (t = 1,2,\cdots,n) \quad (14)$$

$$A_{sum} = \sum A_m \quad (m = 1,2,\cdots,16) \quad (15)$$

Where, X_m is the utility of band m, n is the number of lines, m is the serial number of frequency bands, W_{tm} is the harmonic wavelet packet energy entropy of line t band m.

3.4. Characteristic of Transient Zero Sequence Current

In addition to the load current in the AC grid, exist capacitive current, which caused by the wire-to-ground capacitance, in every phase. Every wire-to-ground distributed capacitance can be equivalent to a lumped capacitance. In the isolated neutral system, the sum of three-phase capacitive current equal to zero, when the network is symmetrical. But, in fault phase the capacitive current flows from the fault line to the bus bar, when the small current grounding happened. The capacitive current flows from the bus bar to the fault line in sound phase when the small current grounding happened. The directions are opposite. [1] The magnitude of capacitor current in fault line's fault phase, which flows from the fault line to the bus line is equal to the summation of capacitor current in all sound lines' correspondence phase. Accordingly, the fault line can be selected by comparing about polar and amplitude of decomposition coefficients in the feature frequency band.

Line selection method can be summarized as the following steps:

(1) Obtain the transient zero sequence current signal of each line and harmonic wavelet packet decomposition of the transient zero sequence current signal.

(2) Calculate the harmonic wavelet packet energy entropy of each band for each line.

(3) If the energy entropy distribution of each line is the same, the band is selected as the characteristic frequency band, and the utility value of each frequency band needs to be calculated if the maximum frequency band of the energy entropy is not the same. The maximum utility value band is selected as the characteristic frequency band.

(4) Compare the relationship of polarity and amplitude of the harmonic wavelet packet decomposition coefficients in the feature frequency band.

4 Simulation and Analysis

4.1. Simulation Model

Use Matlab power system block toolbox to build up a small current grounding system,see as Figure 2.

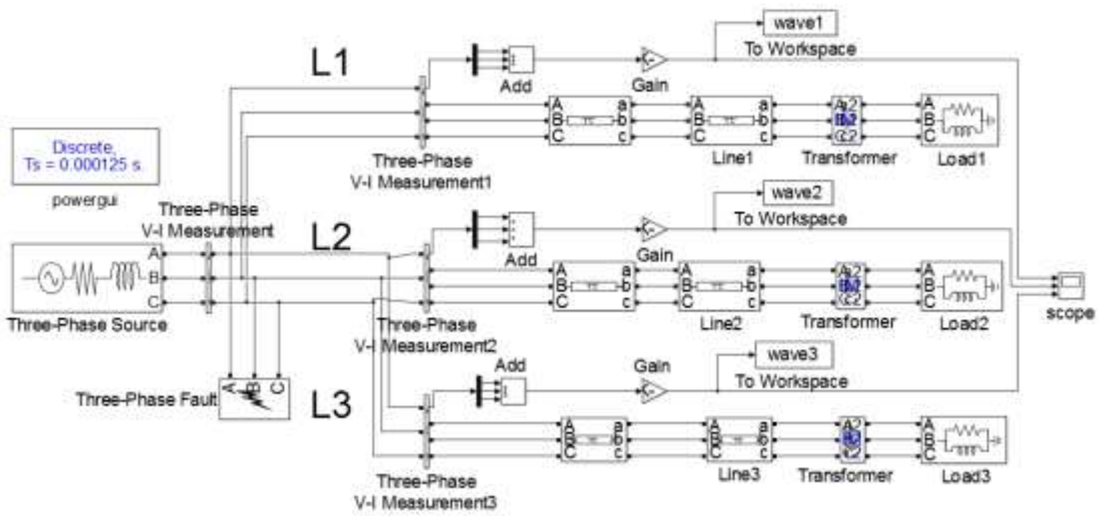

Figure 2. 35KV Isolated Neutral System Simulation Model

This article adopts bus bar with 3 lines system. Simulation parameters set: three-phase power supply voltage of 35KV. Lines using lumped parameter model (3-phase pi section line), the lengths is 10km, 20km, 40km, respectively. Use 3-phase Fault modules to simulate single-phase ground faults [17]. Think about that the spectral range of transient capacitive current's free oscillation frequency mainly from $0\,Hz$ to $3000\,Hz$ [18]. According to Nyquist sampling theorem, set sampling points to 8000 and the powergui parameters Ts is 1.25e-4. Start time is $0\,s$. End time is $0.063875\,s$; The solver select Variable step, Ode23tb; step size is auto, relative tolerance is 0.001, and absolute tolerance choose auto.

4.2. Fault Line Selection Method

Case1:Fault phase:A, fault time:0.005 s , phase angle at 0s:30°,location: L_1 ,8 Km from bus bar, fault conditions:grounding via 500 resistor.

Step1: Setting parameters in the simulink and running the simulation system to get the data of every line under case1. The waveform of transient zero sequence current, as shown in Figure 3

Step2: Calculate the harmonic wavelet packet energy entropy in every scale of the fourth layer, by using formula (10) to (12). The bar chart was used to describe the distribution of harmonic wavelet packet energy entropy in case1, as shown in Figure 4.

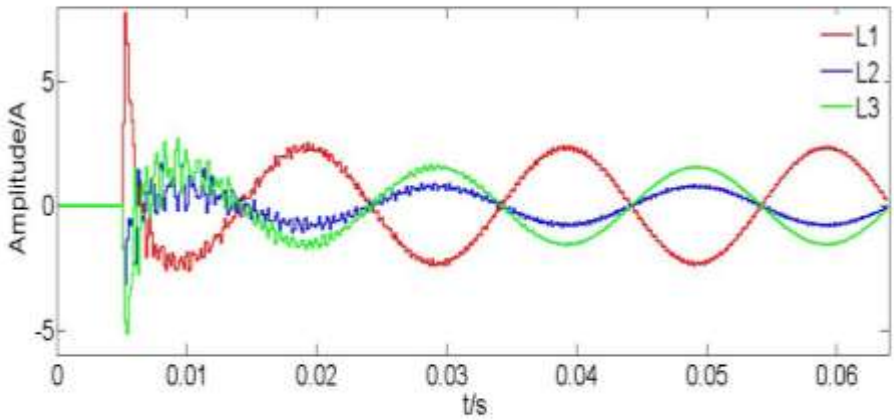

Figure 3.Zero Sequence Current of L_1, L_2, L_3 in Case1

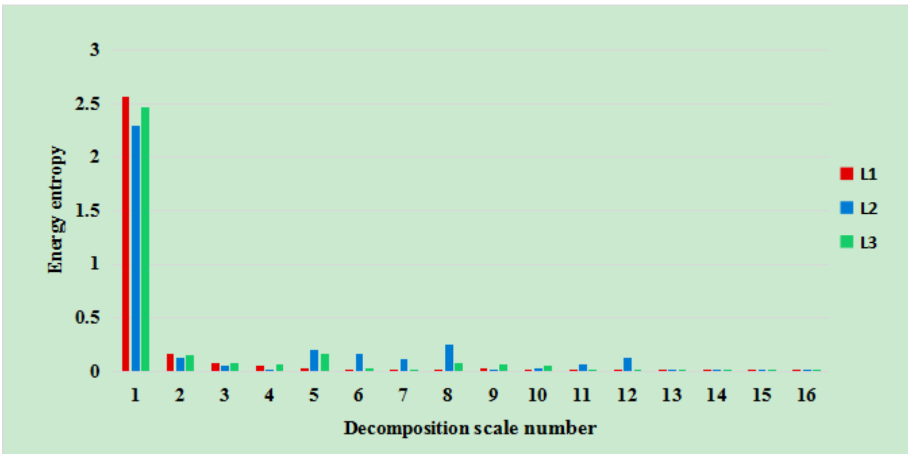

Figure 4.Distribution of Energy Entropy of L_1, L_2, L_3 in Case1

Step3: As figure 4 shown. Obviously, scale 1 have the largest energy entropy. The corresponding frequency band is 0 ~ 250 Hz. Considering the simulation parameters, there are 512 sampling points during simulating time. Due to $N_v = N / 2^{(s+1)}$, take N =512, s =4 into this formula. $N_v = 512 / 2^{(4+1)} = 16$. There are sixteen decomposition sequence points in a frequency band. The situation of every decomposition sequence point in band 1 is shown in Figure 5.

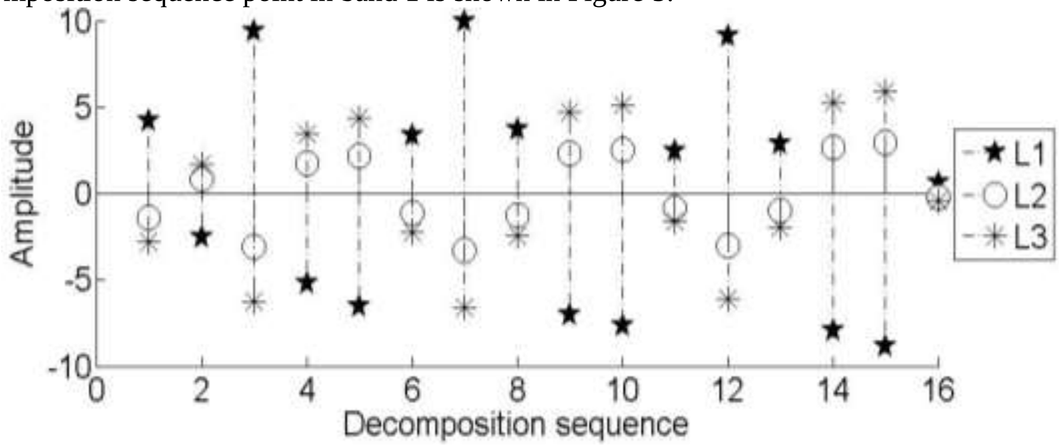

Figure 5. Decomposition Coefficients and Sequence Points in Band 1

Step4: Line L_1, which uses five-pointed star-shaped black dots to represent is higher than sound lines L_2 、L_3. The polarity of L_1 is different to the polarity of L_2 and L_3. Thus L_1 was selected as the fault line. The result of line selection by using harmonic wavelet packet energy entropy theory, in case1 is correct.

Case2:Fault phase is A, fault time:0.005 s, phase angle at 0 s :10°, location: bus bar, fault conditions metal grounding.

Step1: Get the data of ever line under case2. The waveform of transient zero sequence current, as shown in Figure 6. Due to voltage is close to the voltage peak in fault phase. When single-phase grounding fault happens, capacitor discharge. The magnitude of transient zero sequence current is large in the fault line. Generate a strong and complex transient process. And accompany by higher oscillation frequency [19].

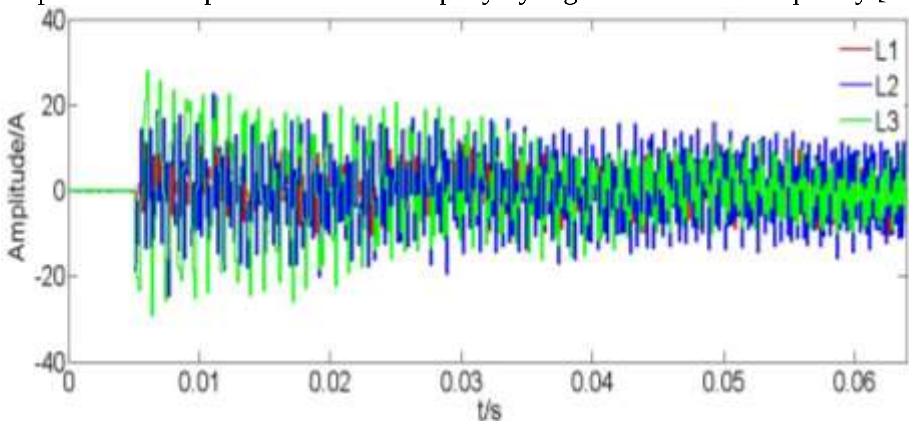

Figure 6. Zero Sequence Current of L_1, L_2, L_3 in Case2

Step2: Calculate the harmonic wavelet packet energy entropy in every scale of the fourth layer by using formula (10) to (12). Use bar chart to describe the distribution of harmonic wavelet packet energy entropy in case2, as shown in Figure 7.

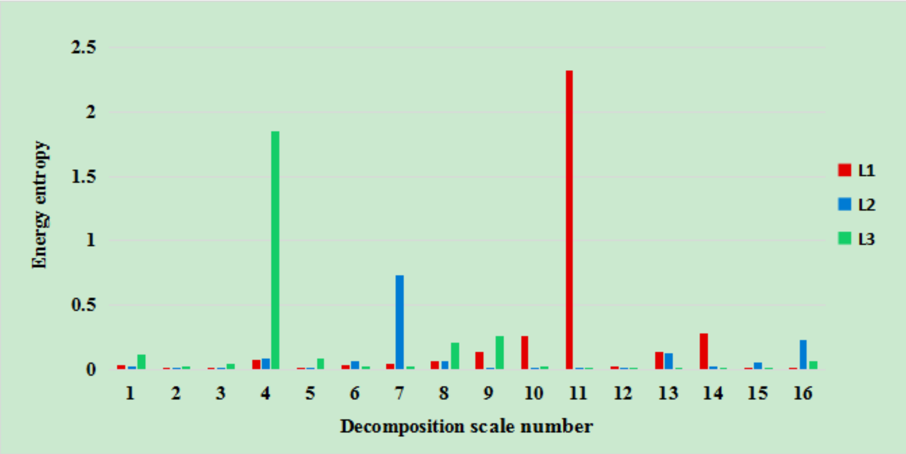

Figure 7. Distribution of Energy Entropy of L_1, L_2, L_3 in Case2

Step3: Seen from Figure 7. The distribution energy entropy is not always the same. The largest energy entropy band of L_1, L_2, L_3 is 2250~2500 Hz, 1250~1500 Hz, 750~1000 Hz respectively. In views of this situation, which does not have the same maximum entropy energy band. Using formula (13) to (15) to calculate the utility value of each band under the fourth layer. And the utility value of each band is represented by a bar chart, as shown in Figure 8.

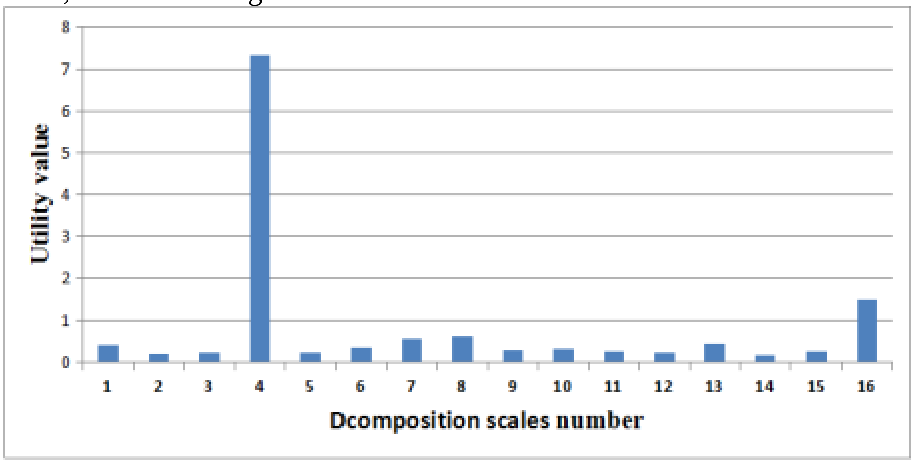

Figure 8. Utility Value of Every Band in Case2

It can be seen from Figure 8. The fourth band (750~1000 Hz) has the largest utility value. So, choose the fourth band as feature frequency band can provide more useful information to select the fault line. The situation of every decomposition sequence point in band 4 is shown in Figure 9.

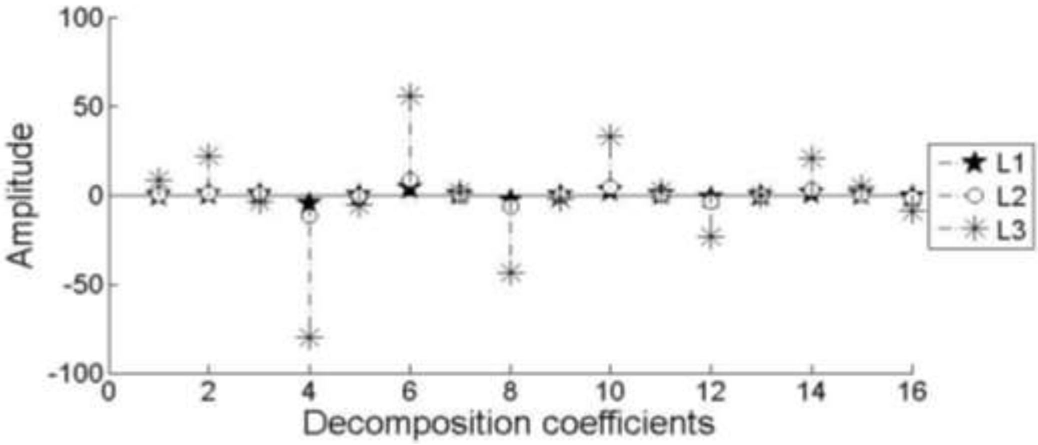

Figure 9. Decomposition Coefficients and Sequence Points in Band 4

Step4: It can be seen from figure 9. The polar of decomposition coefficients in every decomposition sequence point are identical. Thus, determined as bus fault. The result of line selection by using harmonic wavelet packet energy entropy theory, in case2 is correct.

5. Conclusion

Harmonic wavelet packet is used to decompose the transient zero sequence current of each line and calculate energy entropy for each scale. If the maximum energy entropy of scale for each line is same, the maximum band of energy entropy should be selected to the feature frequency band. To the case of difference in the maximum energy entropy band of each line, the method for selection of feature frequency band which compared by each line energy entropy utility value in different frequency bands is present. The selection of lines is compared with polarity and magnitude of decomposition coefficients of harmonic wavelet packet in feature frequency band. Simulation cases show that the fault line is correctly selected by this method.

Acknowledgments

This work is supported by National Nature Science Foundation of China under Grant 61372195, 61304069, 61371200 and the Scientific Research Fund of Liaoning Provincial Education Department under Grant L2014517, L2013494.

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References

[1] Y. D. Xue, B. Y. Xu and Z. R. Feng, "The Principle of Directional Earth Fault Protection Using Zero Sequence Transients in Non-solid Earthed Network", Proceedings of the CSEE, **(2003)**.

[2] J. F. Dai and Y. X. Zhang, "Study on Adaptively Choosing Fault Line Under Single-Phase to Ground Fault Based on Analysis of Multi-frequency Bands", Proceedings of the CSEE, **(2003)**.

[3] F. Lu, Y. P. Lui and F. Yu, "Fault Line Selection in Non-solidly Earthed Network Based on Phase-frequency Characteristic and Multi-frequency Band Analysis", Automation of Electric Power Systems, vol. 31, no. 4, **(2007)**, pp. 76-79-84.

[4] X. Li, J. L. Li and C. L. Zhang, "Detecting a Fault Line under a Single-Phase to Ground of Distribution Network Based on Analysis of Multi-frequency Bands", Journal of Chong qing University, vol. 31,no. 10, **(2008)**, pp. 1143-1148.

[5] Y. Li and H. B. Liao, "A New Scheme to Faulty Line Selection Based on Wavelet Packets Technology and Correlation Analysis", Journal of Anhui Science and Technology University, vol. 25, no. 4, **(2011)**, pp. 49-52.

[6] J. M. Ding, J. H. Lin and Y. Ren, "Real-Time Diagnosis of Bearing Faults Based on Harmonic Wavelet Energy Entropy", Journal of Mechanical Strength, vol. 33, no. 4, **(2011)**, pp. 483-487.

[7] J. Tang, L. Fan and X. X. Zhang, "Multi-Scale Feature Parameters Extraction of GIS Partial Discharge

Signal with Harmonic Wavelet Packet Transform", Transactions of China Electrotechnical Society, vol. 30, no. 3, **(2015)**, pp. 250-257.
[8] S. C. Wang, H. Han and Z. N. Li, "Adaptive Harmonic Wavelet Packet Transform and Its Application to Machine Fault Diagnosis", Transaction of Chinese Society for Agricultural Machinery, vol. 30, no. 10, **(2007)**, pp. 174-177.
[9] Z. Y. He, Y. M. Cai and Q. Q. Qian, "A Study of Wavelet Entropy Theory and Its Application in Electric Power System Fault Detection, "Proceedings of the CSEE, **(2005)**.
[10] Z. Y. He, Z. G. Liu and Q. Q. Qian, "Study on Wavelet Entropy Theory and Adaptability of Its Application in Power System", Power System Technology, vol. 28, no. 21, **(2004)**, pp. 17-21.
[11] Y. Ma, "Study on Fault Line Selection of Small Current Grounding System Based on Harmonic Wavelet Packet and Chaosy", Ph D.Thesis, Yanshan University, Qinhuangdao, **(2015)**.
[12] D. E. Newland, "Harmonic wavelet analysi", Proc R SocLand, **(1993)**.
[13] D. E. Newkand, "Ridge and phase identification in the frequency analysis of transient signals by harmonic wavelets", Journal of Vibration and Acoustics, vol. 121, no. 2, **(1999)**, pp. 149-155.
[14] Z. C. Huan, Y. Zhong and C. L. Li, "A Method of Single Phase-to-ground Faulty Line Selection Based on Harmonic Wavelet", Electrical Measurement & Instrumentation, vol. 49, no. 1, **(2012)**, pp. 22-26.
[15] W. B. Zhang, X. J. Zhou and Y. Lin, "Harmonic Wavelet Package Method Used to Extract Fault Signal of a Rotation Machinery", Chinese Journal of Vibration and Shock, vol. 28, no. 13, **(2009)**, pp. 89-89+97+201.
[16] G. J. Tang and F. Y. Deng, "Compound Fault feature Separation Method of Rolling Element Bearing Based on Improved Harmonic Wavelet Packet Decomposition", Chinese Journal of Scientific Instrument, vol. 36, no. 1, **(2015)**, pp. 143-151.
[17] Y. S. Zhou, Z. Peng and X. Y. Wei, "Matlab Simulation on Single-phase-to-earth Faultof Smal l Current Grounding Power System", Proceedings of the CSU-EPSA, **(2009)**.
[18] Y. H. Xing, H. J. Wang and Y. P. Lu, "Faulty Line Selection in Non-solid Earthed Network Based on Zero Sequence Frequency Characteristic of Transmission Lines", Electric Power Automation Equipment, vol. 26, no. 4, **(2006)**, pp. 59-62.
[19] W. Q. Tao, H. G. Cao and N. H. Yu, "Application of S-transform to Grounding Line Selection of Neutral Point Ungrounded System", vol. 41, no. 3, **(2014)**, pp. 279-284.
[20] J. G. Zhuang and P. Singh, "Information Entropy:Application and Theory", China Water & Power Press, Beijing, **(2012)**.

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