TELKOMNIKA, Vol.11, No.11, November 2013, pp. 6746~6754
e-ISSN: 2087-278X

Design of New Transformer Protection Device Based on Wavelet Energy Entropy-Neural Network Theory and FPGA

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Abstract

Transformer differential protection may be of malfunction at the emergence of inrush current, and it will affect the normal operation of the transformer. So the paper puts forward a new application of wavelet energy spectrum entropy-neural network theory in transformer microcomputer protection, in which the multi-resolution analysis of wavelet transform and information entropy technology are combined firstly and forms a new conception named wavelet energy spectrum entropy, and it will be put into neural network theory as the feature vector, forms the new algorithm in the end. This method decomposes signal through wavelet transform, and extracts the high frequency part of energy in each scale of wavelet transform from inrush current signal and the short circuit current signal, and calculates the wavelet energy entropy value, which will be as the input feature vector of modified BP neural network. And this feature vector is used as training characteristic value for training in BP neural network. According to the measured data of the system, it has achieved good effect. At the same time, for the large amount of calculation and the high requirements of signal sampling rate in wavelet energy entropy-neural network algorithm, a new idea which uses the high-speed hardware platform of FPGA to realize the algorithm application is put forward, and it will break the bottleneck of traditional microcomputer protection that the MCU would not give consideration to both the speed and the accuracy of the protection at the same time.

Keywords: *wavelet energy entropy, neural network, FGGA (Field programmable Gate Array), inrush current, transformer protection.*

1. Introduction

Transformer is an important equipment of electric power system, and it mostly adopts the longitudinal differential protection as the main protection. The key problem of this protection is how to identify inrush current and short-circuit current of internal fault correctly. The traditional solutions have the following methods: Second Harmonic Brake Method, Voltage Braking Method, Intermittent Angle Method, Magnetic Pass Characteristic Principle Method and Equivalent Circuit, etc. The principle of Second Harmonic Brake Method is relatively simple, which is easy to realize by microcomputer. But with the enlargement of the power grid scale, the increase of the voltage levels and the capacity of the single transformer, the resonance makes the second harmonic contents of short-circuit current increase significantly when the transformer has serious internal faults. And it likely causes the delay action of transformer differential protection which uses the second harmonic brake as the characteristic of protection [1]. The hardware cost of Intermittent Angle Method is high relatively [2]. Voltage Brake Principle must understand the system impedance more accurately [3]. Equivalent Circuit Method is unable to realize physically due to the need of knowing the transformer leakage reactance on both sides of transformer. Magnetic Pass Characteristic Principle Method need make assumptions to some transformer parameters, etc.

In recent years, many new algorithms of identifying inrush current have been put forward by domestic or foreign scholars. Reference [4] has extracted intermittent Angle characteristics of inrush current to identify inrush current and short-circuit current by using wavelet analysis, but its reliability is lower when the application field has serious interfere. Reference [5] has come up with a new method of identifying inrush current by the multi-

Received April 18, 2013; Revised July 8, 2013; Accepted July 29, 2013

resolution theory of wavelet on the basis of wavelet transform, and it makes the method not influenced by the setting value of protection. References [6-9] combined wavelet transform and artificial neural network with strong ability of pattern recognition to identify inrush current. These algorithms have better solved the problem of identification inrush current and short circuit current in internal fault, but because of its large amount of calculation, it is difficult to apply in practice. And these articles above have not given the corresponding solutions of hardware design. About the hardware design of transformer microcomputer protection device, simply 8031 or 8051 series single chip microcomputer have been choose as CPU in the early stage. Later, with the development of micro-processing technology, there is the transformer microcomputer protection device with the ARM as CPU. Then reference [10] applies DSP technology to transformer microcomputer protection, and it has improved the processing speed of the microcomputer relay protection. Reference [11] adopts double CPU structure of DSP and MCU compound, and it has greatly improved the reliability of the protection device and the processing speed of microcomputer protection. FPGA has been applied to transformer microcomputer protection in reference [12], and it only gives the hardware framework based on FPGA.

In view of the above problems, the paper presents a concept of wavelet energy spectrum entropy based on the wavelet transform [13], it formed a new algorithm named wavelet energy spectrum entropy - neural network by combining the wavelet energy spectrum entropy with good signal analysis and processing and neural network with strong ability of pattern recognition, and the algorithm has been applied to the transformer microcomputer protection device. For the high requirements of calculating speed of the algorithm, this paper applied FPGA to the hardware realization of the algorithm, and it will break the bottleneck that traditional MCU can't give consideration to both speed and the accuracy of the protection.

2. Theoretical Analysis of Transformer Inrush Current

When the transformer has normal operation or external fault, the transformer core is unsaturated, the magnetic inductance of the winding is very great, the field current value is very small, and it is not more than 2%~5% of current rating. And when the transformer no-load switching or the voltage recovery after the external fault cleared, the transformer core would be saturated, excitation inductance would be smaller, and it will produce a lot of transient excitation current which can achieve 4~8 times of the rated current that is called inrush current. For the primary protection of transformer, differential protection must ensure the selectivity and sensitivity of the protection action, and it is inevitable to face the special problem of excitation inrush current in transformer. The waveform of inrush current is shown in Figure 1.

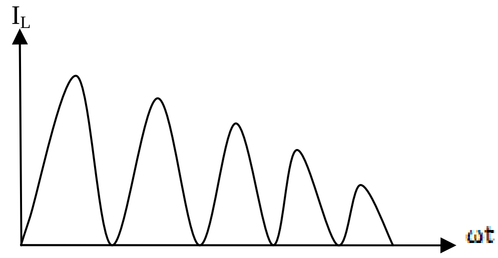

Figure 1. The Waveform of Inrush Current

The data shown in Table 1 is the analysis of several experimental data of inrush current [6]. Thus it can be seen that inrush current has the following characteristics.

(1) Contains so much aperiodic component, and often makes inrush current be on one side of the timeline.

(2) Contains a large amount of high order harmonic, and gives priority to second harmonic.

(3) There are some gaps between the waveform.

Table 1. The Example of the Experiment Data for Inrush Current

Inrush current (%)	Example 1	Example 2	Example 3
The fundamental wave	100	100	100
The second harmonics	40	33	52
The third harmonic	8	7.9	8.8
The fourth harmonic	7	6.8	5.9
The fifth harmonic	6	3	---
The direct current	61	77	64

From the analysis, we can conclude that inrush current is relative to switching initial phase angle, residual magnetism of transformer, saturation magnetic chain and the other factors, such as system impedance, etc.

3. Wavelet Transform and Wavelet Energy Spectrum Entropy

3.1. Wavelet Transform based on the Multi-resolution Analysis

Let $\psi(t)$ is the basic wavelet function, $a \subset R$ is the dilation factor, $b \subset R$ is the shift factor. And for the signal $f(x) \subset L^2 R$, the continuous wavelet transform is as follows:

$$W_f(a,b) = \langle f, \psi(a,b) \rangle = |a|^{-1/2} \int_R f(x)\psi(\frac{x-b}{a})dx \quad (1)$$

In the formula, $\psi(a,b) = |a|^{-1/2} \psi(\frac{x-b}{a})$

For the continuous wavelet function above, the length of discrete signal is n, and it is processed by FFT algorithm, then the signal will pass through the high-pass filter and low-pass filter, the details component of the original signal and the approximate component will be got respectively, the approximate component of the signal will be decomposed sequentially, pass through the high and low pass filter again. When suitable wavelet base function and the number of decomposition layers is chosen, the original signal is decomposed by scale $j = 1, 2, 3...$ (j is the maximum decomposition scale), then $D_1, D_2, D_3, ..., A_J$ will be got finally. Among them, $D_1, D_2, D_3, ..., A_J$ and $D_1, D_2, D_3, ...D_{j-1}$ are the detail components of high frequency and approximation component s of low frequency of the signal [14].

$$\begin{cases} A_{j+1} = H_i \_ DA_j(k) \\ D_{j+1} = L_0 \_ DA_j(k) \end{cases} \quad (2)$$

Each layer coefficient after decomposition will be reconstructed by the wavelet transform coefficient, the high-pass and low-pass filter coefficient after reconstruction is $H_i^* \_D$ and $L_0^* \_D$. Among them, $H_i^* \_D$ and $L_0^* \_D$ are the dual operator of $H_i \_D$ and $L_0 \_D$.

$$A_{j-1} = H_i^* D \times D_J + L_0^* D \times A_J \quad (3)$$

3.2. Information Entropy

The concept of entropy was first applied to the thermodynamics by R. Clausius. In the second law of thermodynamics, entropy is a state function, and that is in the isolated system, the irreversible process entropy will increase and the eversible process entropy will be changeless. It reveals that all the spontaneous direction of the irreversible procedure in internal system is the direction of entropy increasing. Then, Shannon who is the founder of the information, introduced the concept of entropy into the information theory in 1948, and the entropy was used as the information source, enriched the concept of entropy, and entropy has become a measure of uncertainty degree of system state since then.

Let X be a random independent variable, and its probability density function is $p(x)$. Let $I(x)$ be the amount of information on the unit amplitude. That is:

$$I(x) = \ln \frac{1}{p(x)} = -\ln p(x) \quad (4)$$

It is an uncertainty measure of the value of random variable X, and it is another kind of simple probability measure.

Entropy is defined as follows.

$$H(x) = -\int p(x) \ln p(x) dx \quad (5)$$

It is the uncertainty measurement of random variable, or is the average amount of information entropy, and the uncertainty of entropy is greater, the entropy value is greater too.

3.3. Wavelet Entropy [13]

With the combination of wavelet transform and information entropy, wavelet energy spectrum entropy of the signal can be got. Let $E = E_1, E_2, ..., E_m$ be the wavelet energy spectrum entropy of $x(t)$ in m scale, then it can form a division to the ability of the signal in the domain E scale. By the characteristic of orthogonal wavelet transform, we can know that in a certain time of the window (the window width is $w \subset N$), signal total power E is equal to the sum of each component of the power E_j. Let $p_j = E_j / E$, then $\sum_{j=1}^{n} p_j = 1$, so we define the corresponding wavelet energy spectrum entropy W_{EE} (Wavelet Energy Entropy) as follows:

$$W_{EE} = -\sum_{j=1}^{n} p_j \log p_j \quad (6)$$

In the formula, $E_j = \sum_k |D_j(k)|^2$

4. Neural Network

The network structure of probabilistic neural network is relatively simple, and it is easy for training, so it is widely used in the problem of pattern recognition. And the most widely used of neural network theory is the three layer neural network with feed forward, it can form arbitrarily close approximation to arbitrary nonlinear continuous map, and it has very strong nonlinear approximation ability, generalization capability and fault tolerance ability. BP neural network is adopted in this paper, which consists of input layer, middle layer and output layer. Middle layer is the hidden layer too, it can be a layer or more layers. The input layer calculates the distance between input vector and the training sample firstly, and its output is the close degree of them. After the calculation of action function in the hidden layer, it will be send to the output node, and the output value will be got. With the comparison of output value and the desired output value, it will be back transmitted if there is an error, and the weight value and closed value will be modified. The above process is repeated, until the output value meets the requirements [8]. The structure of BP neural network is shown in Figure 2.

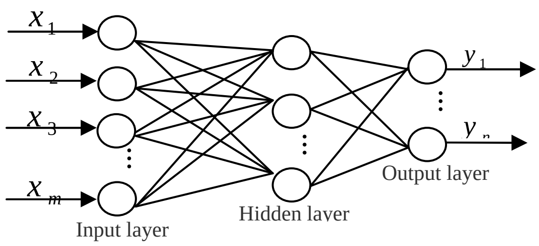

Figure 2. The BP Neural Network Model

5. The Application of Wavelet Energy Spectrum Entropy and Neural Network in Transformer Protection

The basic principle based on the wavelet energy spectrum entropy and neural network to identify the transformer inrush current is that combining with the characteristics of intermittent phenomenon presented by inrush current waveform, it extracts feature value by wavelet theory, and after the wavelet decomposition and coefficient reconstruction, it calculates the wavelet energy entropy value of each layer in coefficient, which will be as the input value of neural network, and after the processing by neural network system, then determines whether the inrush current or not. Except the base wave and non-synchronous component, the inrush current contains a lot of high order harmonic current which is second harmonics mainly, and sometimes there is a part of the three harmonic. While internal short circuit current mainly contains base wave, and high order harmonic content in it is lower [15].

The realization of this method is shown in Figure 3.

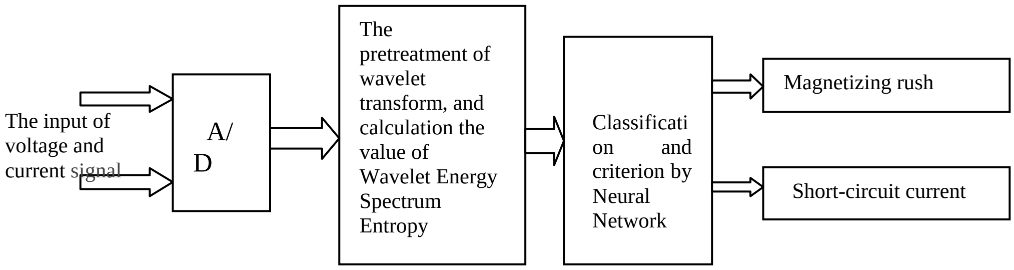

Figure 3. The Diagram of Identification Method of Inrush Current by Wavelet Energy Entropy Neural Network

5.1The Establishment of Simulation Model.

PSCAD/EMTDC software is adopted to simulate the inrush current of transformer in the paper, and the sample of wavelet energy spectrum entropy-neural network will be extracted from it. Simulation model of three-phase inrush current in transformer is established by classical approach in PSCAD/EMTDC library.

The simulation model is shown in Figure 4.

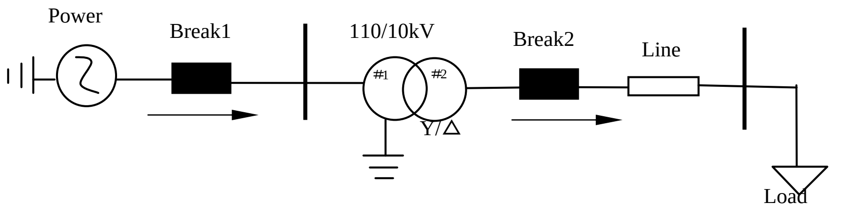

Figure 4. The Simulation Diagram of No-load Switching of Three-phase

In Figure 4, R/R-L model is adopted as the equivalent power, the value of Series Resistance and Parallel Resistance is supposed as 1Ω, the value of Parallel Inductance is 1H, the rated voltage is 110kV. The saturation characteristic transformer is selected, whoescapacity is 160MVA, the ratio is 110kV/10kV, and the load is 100MW. T-line model of transmission line is adopted. The frequency of the system is set as 50Hz. Circuit breaker BREAK1 and BREAK2 are set to realize the circuit switching of power line, BREAK2 is set as always opening, and BREAK1 will be no-load switched on at 0.1 s.

This paper mainly conducted the simulation for several kinds as the following.

1) Inrush current is produced by changing the initial phase Angle when switching on. The simulation is conducted when the transformer remanent magnetism is 0, and the initial phase Angle of switching on is 0°, 30°, 60°, 90°, 120° and 150° respectively.

2) Inrush current is produced by changing remanent magnetism. The change range of remanent magnetism is 0~70% of rated voltage leakage peak.

3) Inrush current is produced by different short circuit type. The types of short circuit are A, B, C single-phase ground short circuit, AB、BC、CA two-phase ground short circuit, ABC three-phase ground short circuit, AB、BC、CA inter-phase short circuit and ABC three-phase ground short circuit.

Figure 5 is the simulation waveform of inrush current, when initial phase angle of A phase is 0, and remanent magnetism is (0,0,0).

Figure 6 is simulation waveform of three-phase short-circuit current.

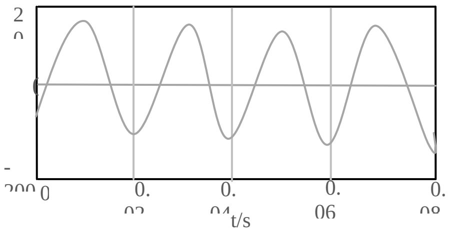

Figure 6. Simulation Waveform of Three-phase Short-circuit Current

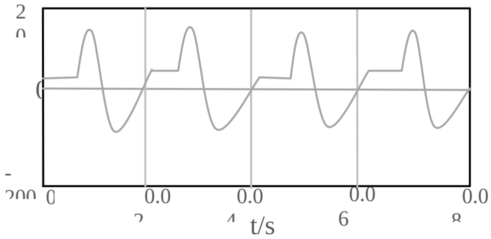

Figure 5. Simulation Waveform of Inrush Current

5.2 The Choice of Wavelet Basis

According to the discussing of reference [16], the wavelet support length is 5~9 that is selected in most applications usually. If the support length is too short, the signal energy is not easy to be concentrated. If the support length is too long, there will produce the boundary problem easily. We find that db6 wavelet is the most ideal after many repeated tests. So this paper chooses db6 wavelet to extract energy characteristic value.

In order to ensure the accuracy of sampling, sampling frequency in the paper is set to 6400Hz. After the decomposition and reconstruction by wavelet transform coefficient, the wavelet energy entropy of each layer coefficient is calculated respectively according to formula 1. Then the calculated wavelet energy entropy value is put into neural network to determine the running state of the current system.

This paper chose db6 wavelet to decompose sampling signal, and three layer BP neural network as reconstruction neural network, the hidden layer chose S type hyperbolic tangent function Tansig. According to the design requirement, the input layer has six input units, the output layer has one output unit, and the number of hidden layer nodes is chosen as 12 according to the empirical formula.

5.3. Analysis of Experimental Data

Table 2 gives the wavelet energy spectrum entropy value which is refactoring of AB phase differential current by 6 layers wavelet transform at the time of inrush current, turn-to-turn fault and internal fault.

Table 2. The Value of Wavelet Energy Entropy in Various Cases

Layer- number of decomposition / The value of Wavelet Energy Entropy	D6	D5	D 4	D 3	D 2	D 1
Differential current between A and B-phase When the excitation inrush current of transformer appearing	119.112	12.1479	1.00428	0.11324	0.03789	0.00856
Differential current between A and B-phase When the inter-turn fault of transformer appearing	89.6546	4.5680	0.89571	0.20436	0.00984	0.00112
Differential current between A and B-phase When the internal fault of transformer appearing	0.90483	0.71125	0.32149	0.04589	0.00247	0.00054

From the data in the table above, all layers of the wavelet energy entropy value after inrush current reconstruction are greater than the short circuit current value. It shows that the wavelet energy spectrum entropy value of inrush current and short-circuit current have obvious difference a few previous cycles of generation. That is the wavelet energy spectrum entropy method can effectively distinguish inrush current and short circuit current value.

In addition, because the wavelet energy entropy value is chosen as feature vector, for the three kinds of two phase differential current, they all formed a complex nonlinear mapping between inrush current and short circuit current respectively, which is not easy to find the right setting valve to distinguish the two types of current through conventional method. But the artificial neural network has natural advantages in the treatment of complicated nonlinear relation, which is a kind of ideal classifier. So the characteristic value above is send into neural network for processing.

6. Numerical Examples

Because this paper established the neural network for three-phase power system, every two phase differential current are decomposed by wavelet and will get a characteristic vector made by 6 elements. So the characteristic vector group consists of 18 elements can be got, which is the input variable of neural network. In order to ensure the accuracy of the training results, the training sample should include inrush current and short circuit fault current (all take differential current) as far as possible. In the training sample selection, the paper considers the following several kinds of situations intensely: 9 running state of transformer, changing the initial phase Angle when switching on and changing the transformer remanent magnetism.For the permutation and combination of the factors above, we can get 216 transformer working conditions. The first 4 period of current signal is decomposed and reconstructed by wavelet transform, and the characteristic parameter is extracted to calculate the wavelet energy spectrum entropy value and the value is made as the input of neural network, which forms the training samples and testing samples of neural network. The total number of samples is 864, and among them, 700 samples are put into neural network for training, another 164 samples is used for testing after the neural network training.

Test results are shown in Table 3 (only 7 groups are selected).

Table 3. The Training Results of Neural Network

Running State of Transformer	Initial phase angle when switching	Residual magnetism	Value of expectation	Value of actual output	Decision outcome
No-load switching	0°	0	0.2	0.1997	inrush current
No-load switching	30°	0.5	0.2	0.2010	inrush current
No-load switching	120°	0.2	0.2	0.2005	inrush current
No-load switching in inter-turn fault of B phase (6%)	90°	0.1	0.8	0.7958	internal fault
Ground short circuit in C phase	150°	0.6	0.8	0.8001	internal fault
Inter-phase short circuit between B and C phase	60°	0.7	0.8	0.8005	internal fault
Inter-phase short circuit between A, B and C phase	30°	0	0.8	0.7991	internal fault

From the table above, it can clearly see that the probabilistic neural network after training can identify inrush current and internal short circuit current accurately and correctly, so probabilistic neural network can identify fault types of transformer effectively.

7. The Algorithm of Wavelet Energy Entropy-Neural Network Realized by FPGA

FPGA (Field Programmable Gate Array) has the advantages of field programmable ability, such as the low power consumption, the high stability and easy to upgrade, etc. It is a kind of chip facing future and very suitable for high-end digital logic circuit design field which has high speed and high density, and it is a device that can realize large-scale logic circuit.

Due to the wavelet energy entropy-neural network algorithm requiring higher sampling frequency of the system, and the microcomputer relay protection demands higher real-time, it is difficult for the traditional protection devices to give consideration to both speed and accuracy of protection. But the FPGA includes almost all characteristics of digital signal processor (DSP), such as in-line multiplier, special calculation routines and a large number of random memories etc. And with the parallelism of FPGA, it is about 500 times faster than the fastest DSP chip or more, so it can better meet the high-speed data processing of microcomputer protection [12]. The hardware design of transformer differential protection based on FPGA is shown in Figure 7.

In the structure mode of Figure 7, FPGA integrated data acquisition, microcomputer protection (it can realize wavelet-neural network algorithm and FFT algorithm, etc.), measurement, communication, scheduling, wave record and other functions. It is the special chip of System-on-Chip for transformer digital protection and it can monitor various operation parameters of power transformer in time, provide all kinds of microcomputer protection for transformer, concentrate many functions in one, such as wave record, RS-232, CAN bus communication, man-machine interface and other additional functions.

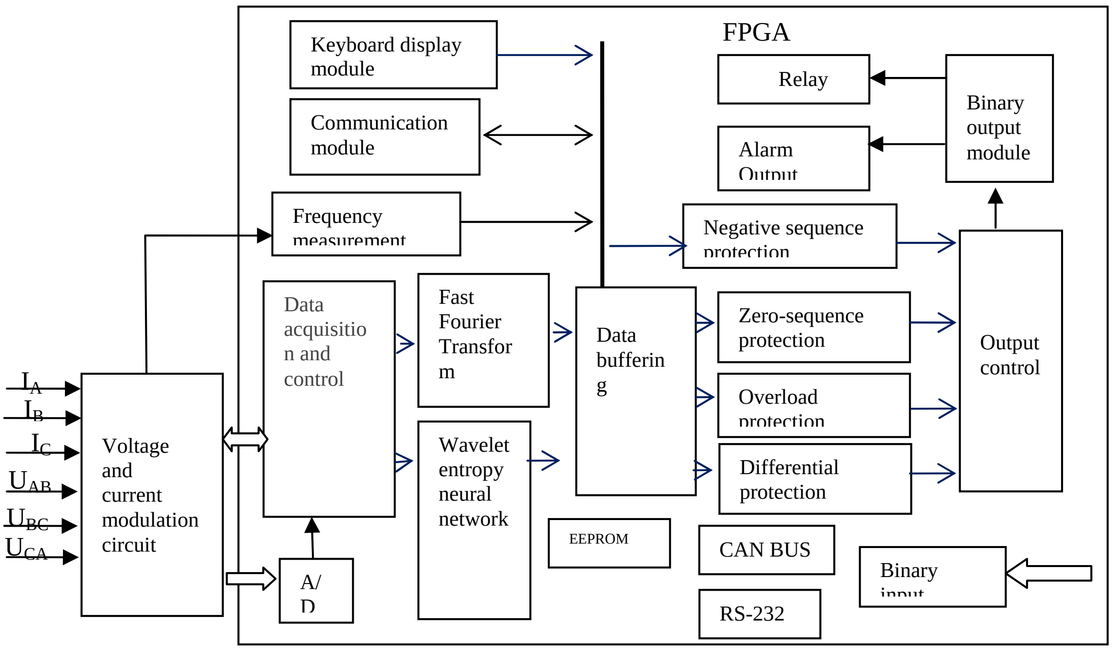

Figure 7. Hardware Design of Transformer Differential Protection based on FPGA

8. Conclusion

This paper put forward a new application of neural network theory based on wavelet energy spectrum entropy pretreatment in transformer microcomputer protection, built the inrush current simulation model of three-phase transformer through the PSCAD/EMTDC software, extracted the sample for wavelet energy entropy-neural network, and after the sample pretreated by the wavelet energy entropy, obtained a large number of training samples, then put into BP neural network for training. The training results showed that this method can accurately identify inrush current and short-circuit current, so it provided a new idea for the development of identifying inrush current and short-circuit current. In hardware design, because of the heavier calculation of wavelet energy spectrum entropy-neural network theory, the paper applied the practical field programmable gate array (FPGA) with flexible structure and better compatibility to the hardware realization of the algorithm, and it has improved the calculation speed and accuracy of the algorithm greatly. Simulation results demonstrated the practicality, computational accuracy and efficiency of the system and it can be applied to the actual system.

The next direction of this system is that in the experimental data extraction, through the method of combining dynamic model test and extracting field data, making the training sample expansion as far as possible and reducing the differences between the simulation data and the experimental data.

Acknowledgements

The paper is supported by the following projects:
(1) Natural Science Foundation of China (61071087).
(2) National Natural Science Foundation of Shandong province (ZR2011FM018).
(3) National Natural Science Foundation of Shandong province (ZR2012EEM021).

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