Application of chaos and extension theory to fault diagnosis of three-phase synchronous generators

Shiue Der Lu, Meng Hui Wang and Shih Kai Chen

Abstract
This study applied an extension algorithm combined with the Chaos Theory to the fault diagnosis of the three-phase synchronous generator. First, the three-phase synchronous generator is classified, including normal, carbon brush fault, three-phase unbalance, and insulation deterioration, and then by means of hardware measurement circuit and device, electrical signals are measured for each category and a chaotic error scatter map is built through the Chaos Theory to get the chaotic eye coordinates under specific fault categories. Next, the extension algorithm is used to carry out the correlation function and the normalization calculation, evaluating the type of fault to which it belongs. The analysis results show that the proposed method can effectively identify the fault types of three-phase synchronous generators and significantly reduce the amount of feature extraction data, so as to effectively detect the change of fault signals, allowing us to know the operation state of three-phase synchronous generators.

Keywords
Extension algorithm, Chaos Theory, fault diagnosis, three-phase synchronous generator

Introduction
The application of generators in daily life is very broad, such as gasoline engine fuel generator, building emergency diesel generator, hydraulic generator, and so on. The generator is divided into two types: the synchronous generator and the non-step generator. Because of the difference in function and structure, their type of fault is different. In terms of power system security, if a generator fault occurs, then it seriously affects the rear end device system, making generator fault diagnosis and prevention a very important aspect in the research field. The synchronous generator is driven mainly through the original motive to convert the mechanical energy into electrical energy. As far as the type of fault is concerned, the most common fault is carbon brush. Once it occurs, the excitation voltage can no longer be an exciter, resulting in power generation being unable to reach the rated voltage. Under the condition of loading, the current rises due to the fixed power of the generator, resulting in the risk of burnout for power equipment.

The literature includes some research on the detection of generator faults. In Bacha and Chaari, when the three-phase synchronous generator fails, fault analysis is carried out by discrete event simulation. The diagnostic system is used to simulate the time as a sequence of discrete events through the modeling method in order to mark and judge the state of the generator change. This method is mainly used for the analysis of the resistance and non-linear load. If the inductance is loaded, then it affects the accuracy of the diagnosis. Qiang used digital signal processing technology to measure the power factor of the residual heat generator. It mainly synchronized signal processing technology to measure the power factor of the residual heat generator.
measurement for a generator to obtain the data sequence of voltage and current. A discrete Fu Liye transform was then applied to accurately analyze the power factor of the power angle and also to make fault diagnosis for a generator. Nadarajan et al.⁴ applied the extended Kalman filter to detect and diagnose the stator winding faults in a brushless wound synchronous generator and build an experimental platform to measure the three-phase terminal voltage and current. It utilized the Kalman filter to analyze the second harmonic component of the rotor current and compared the root mean square value of the three-phase terminal voltage and current parameter to diagnose the winding fault. Quyessaad et al.⁵ proposed the circuit-coupled finite element analysis method, which is based on the actual internal structure modeling of a synchronous generator. The method was used to accurately simulate the fault current inside the coil and accurately identify the location of the actual fault point. However, this method can only be used for fault diagnosis of stator winding coils because they must be compared with the normal stator winding coils. Gau and Siao⁶ built the information network platform semantic network structure and obtained information on the side of the wind generator through the sensing component, analyzing the signal and type of fault to construct the fault type table. This method is mainly based on the look-up table method for the fault control, and so there is a certain error in the discrimination. Ernani and Azirani⁷ used the hierarchical analysis method to diagnose the short circuit fault and the common fault type of the generator stator winding. Several comparison graphs were generated, and the expert knowledge system was used to identify the fault characteristics of the generator. Hua et al.⁸ presented a method of modeling with wavelet analysis and fuzzy neural network. It is a fault diagnosis of the rotating machinery vibration used in a turbine generator set.

Based on the application of the Chaos Theory and extension diagnosis method, this research targets a three-phase synchronous generator with a rated voltage of 220 volts and a rated speed of 1800 revolutions per minute. The statistics of IEEE related literature classify the fault type of the most frequent accidents, including brush fault, three-phase unbalanced fault diagnosis, and insulation deterioration. The results of simulation analysis show that the proposed method not only has high recognition accuracy but also generates chaotic error through the Chaos Theory, and the Eigenvalues of the walking map and the chaotic eye can effectively reduce the huge amount of electrical data measured. The extension algorithm is used to diagnose the type of fault of the starting motor.

**System structure**

The fault diagnosis of a three-phase synchronous generator in this paper is divided into three main parts: measurement and preprocessing of signals, eigenvalue extraction of chaotic eye coordinates, and extension diagnosis. Figure 1 shows the flowchart of the research system in this article. First, it uses the hardware measurement circuit and the oscilloscope to pick up the generator to be detected, as shown in Figure 2. Through a chaotic dynamic error dispersion diagram produced by the master and the chaotic system of the Chaos Theory, it then obtains the chaotic eye coordinates of the type of fault. Next, the matter-element model is established through the extension theory, and the correlation degree calculation and the identification of the fault types are executed.

The synchronous generator signal in this study is measured by a LeCroy 500 MHz oscilloscope, and the electrical signal acquisition of voltage and current is realized by using a transformer and Holzer circuit.

---

**Figure 1.** System flow chart.
Figure 2 is a circuit diagram of the interception of the oscilloscope signal. Here, $V_{\text{Out}}$ and $A_{\text{Out}}$ are the voltage and current signal measured by the oscilloscope probe.

Figure 2 illustrates a three-phase synchronous generator measurement architecture diagram. The voltage signal measurement of a generator is mainly based on the input voltage range (0 V–220 V) converted to 0 V–6 V voltage signal through the step-down transformer, and then the waveform and value ($V_{\text{Out}1}$ to $V_{\text{Out}3}$) are intercepted by an oscilloscope. The current part is converted to 1 V–10 V voltage signal based on the Holzer component according to the input current range (0.1 A–1 A), and then the voltage value ($A_{\text{Out}1}$ to $A_{\text{Out}3}$) of each phase of the generator is measured by an oscilloscope.

Figure 3 shows the entity diagram of three-phase synchronous generator measurement, including oscilloscope, load box (Y-connected), instrument display machine, three-phase synchronous generator (220 V, 1800 r/min, and 60 Hz), and prime mover. Among them, part of the primary motor is the permanent magnet brushless motor that can drive the rear-end generator to the rated speed (1800 r/min).

**Proposed methods**

**Chaos Theory**

The Chaos Theory is proposed by EN Lorenz, which mainly discusses the instability of non-linear dynamic systems. The simple model operation is constructed through the Chaos Theory to obtain non-periodic results, and when a signal is used in a chaotic system, the chaotic system results in a severe small change in the signal as time changes.9

A master–slave chaotic system is the main system seeking another simple system. Master ($S_{\text{master}}$) and slave ($S_{\text{slave}}$) chaotic systems are shown in equations (1) and (2). After reducing the value of the two systems, the chaotic

![Figure 2. Three-phase synchronous generator signal measurement architecture diagram.](image)

![Figure 3. Entity measurement diagram of a three-phase synchronous generator.](image)
dynamic error caused by the two systems is different. In engineering, the master system is traced by the slave system, and the two-system operation trajectory is gradually adjusted by the controller. The tracking system is a chaotic synchronization system, and this system is widely used in communication encryption as well as biomedical and engineering fields. In a chaotic system, with the change of time, the small amount of change in the characteristic signal creates a more dramatic change by the chaotic system. The chaotic dynamic error system is subtracted through two chaotic systems to extract the dynamic error between the two systems. In the master–slave chaotic system, the master chaotic system and the slave chaotic system are shown in equations (1) and (2) in Tian and Peng:

\[
S_{\text{master}} = \begin{cases} 
\dot{x}_1 = f_1(x_1, x_2, \ldots, x_n) \\
\dot{x}_2 = f_2(x_1, x_2, \ldots, x_n) \\
\vdots \\
\dot{x}_n = f_n(x_1, x_2, \ldots, x_n) 
\end{cases}
\]

(1)

\[
S_{\text{slave}} = \begin{cases} 
\dot{y}_1 = f_1(y_1, y_2, \ldots, y_n) \\
\dot{y}_2 = f_2(y_1, y_2, \ldots, y_n) \\
\vdots \\
\dot{y}_n = f_n(y_1, y_2, \ldots, y_n) 
\end{cases}
\]

(2)

This study notes that \((f_1, f_2, \ldots, f_n)\) belong to a non-linear function. Equations (1) and (2) are subtracted to form an error, and after calculation, the equation of dynamic error is obtained, as shown in equation (3):

\[
\begin{align*}
\dot{e}_1 &= f_1(x_1, x_2, \ldots, x_n) - f_1(y_1, y_2, \ldots, y_n) \\
\dot{e}_2 &= f_2(x_1, x_2, \ldots, x_n) - f_2(y_1, y_2, \ldots, y_n) \\
\vdots \\
\dot{e}_n &= f_n(x_1, x_2, \ldots, x_n) - f_n(y_1, y_2, \ldots, y_n)
\end{align*}
\]

(3)

This paper uses the Lorenz master–slave chaotic system, as shown in equations (4) and (5):

\[
L_{\text{master}} = \begin{cases} 
\dot{x}_1 = \alpha(x_2 - x_1) \\
\dot{x}_2 = \beta x_1 - x_1 x_3 - x_2 \\
\dot{x}_3 = x_1 x_2 - \gamma x_3 
\end{cases}
\]

(4)

\[
L_{\text{slave}} = \begin{cases} 
\dot{y}_1 = \alpha(y_2 - y_1) \\
\dot{y}_2 = \beta y_1 - y_1 y_3 - y_2 \\
\dot{y}_3 = y_1 y_2 - \gamma y_3 
\end{cases}
\]

(5)

After subtracting equations (4) and (5) and after the calculation, the Lorenz master–slave chaotic system error equation of the chaotic system is shown as the matrix of equation (6):

\[
\begin{bmatrix}
\dot{e}_1 \\
\dot{e}_2 \\
\dot{e}_3
\end{bmatrix} =
\begin{bmatrix}
-\alpha & \alpha & 0 \\
\beta & -1 & 0 \\
0 & 0 & -\gamma
\end{bmatrix}
\begin{bmatrix}
e_1 \\
e_2 \\
e_3
\end{bmatrix} +
\begin{bmatrix}
y_2 y_3 - x_2 x_3 \\
y_1 y_3 + x_1 x_3 \\
y_1 y_2 - x_1 x_2
\end{bmatrix}
\]

(6)

In this study, voltage is the main system, and current is the slave system of Lorenz. Using equations (1) and (2) chaotic scatter plots, we define the two centroid points in the scatter graph as chaotic eyes. The numerical value of
the chaotic eye coordinates is taken as the fault characteristic value of the extension theory. The adjustment error coefficients are, respectively, \( \alpha = 10 \), \( \beta = 28 \), and \( \gamma = (-8/3) \).\(^{12}\)

**Extension diagnosis algorithm**

The chaotic eye coordinates obtained by the Chaos Theory are used as the eigenvalues and are classified by the Extension Diagnosis Method. In the Extension Diagnosis Method, there are two mathematical methods, “extension set” and “matter-element theory,” used as tools for the application of extension evaluation. The extension evaluation method accumulates a number of databases from experiments, dividing one thing into a variety of sets, which are given by experts to set the level of each set. The data of the things to be evaluated are then calculated by correlation and normalization, and the results are compared with the extension correlation of each set. If the value of the correlation is closer to 1, then the degree of data evaluation conforms better with the set of the rank. The steps of its specific fault identification are explained as follows.\(^{13}\)

Step 1: Definition of the extension classical domain is shown in equation (7). The theory is to divide \( R \) into a set of \( k \) levels, which is called an extension classical domain. Here, \( N_k (k = 1–m) \) represents the name of the individual element of the set of \( k \) classes divided, and all the features of the matter name are represented by \( C \), which is in the distribution of \( i \) feature at the \( k \) level. The size of the eigenvalue is \( a_{ki} (i = 1–n) \), representing the maximum value of the level of the matter-element, while \( b_{ki} (i = 1–n) \) represents the minimum value of the level of the matter

\[
R_k = \begin{bmatrix}
N_k & C_1 & < a_{k1}, b_{k1} > \\
C_2 & < a_{k2}, b_{k2} > \\
\vdots & \vdots \\
C_n & < a_{kn}, b_{kn} > 
\end{bmatrix}
\]  \(^{(7)}\)

Step 2: After determining the matter to be measured, the set of features must be equal to the number of the collection of the classical domain and the joint domain, which is called the matter to be measured, as shown in equation (8)

\[
R = \begin{bmatrix}
q & C_1 & x_1 \\
C_2 & x_2 \\
\vdots & \vdots \\
C_n & x_n 
\end{bmatrix}
\]  \(^{(8)}\)

Here, \( q \) is the type of the generator to be measured and \( x_i (i = 1,2,\ldots,n) \) is the chaotic eye eigenvalue data of \( C_i (i = 1,2,\ldots,n) \), which are the specific data for testing things to be measured.

Step 3: Set the weight value of each characteristic value, and \( R \) is made up of the features of each group \( C_i \). Its characteristics also have different influences on the object. This step determines the weight of each feature by using the relation of weight coefficient, and the sum of all weight coefficients is equal to 1, as shown in equation (9)

\[
\sum_{i=1}^{n} W_i = 1
\]  \(^{(9)}\)

Step 4: Calculate the magnitude of the degree of correlation between the data to be measured and each category, which refers to a distance difference between an eigenvalue \( x_i \) for the central point of a classical domain or a node and a distance difference between center point and upper and lower limits in a matter to be measured, as shown in equation (10)

\[
\rho(X_i, X_{ki}) = \left| x_i - \frac{a_{ki} + b_{ki}}{2} \right| - \frac{b_{ki} - a_{ki}}{2}
\]  \(^{(10)}\)
Step 5: Calculate the correlation function. If the calculation of the classical domain and the pitch distance has been completed, then the operation of the joint function can be performed. The value of the associated function is calculated by equation (12), and equation (13) is added to obtain the degree of membership of the subject, and thus the category of categorization can be clearly defined from this step

\[ k_k(x_i) = \begin{cases} 
-\rho(x_i, X_{k'}) / |X_{k'}|, & x_i \in X \\
\rho(x_i, X_{k'}) / \rho(x_i, X_{k''}) - \rho(x_i, X_{k'}), & \text{other} 
\end{cases} \]  

(11)

\[ k_k(q) = \sum_{i=1}^{n} W_i k_k(x_i) \]  

(12)

Step 6: Normalization. After operating the relative value of the correlation degree, normalize it by equation (14) so that the correlation falls directly between <1,–1>.

\[ k_k(q) = \frac{2k_k(q) - k_k(q)_{\text{max}} - k_k(q)_{\text{min}}}{k_k(q)_{\text{max}} - k_k(q)_{\text{min}}} \]  

(13)

Step 7: Determine the type of things to be evaluated. If \( k_k(q) \) is equal to 1, then the extension to determine the correlation belongs to the evaluation results of category \( k \), and the other sets vary depending on the correlation degree. The stronger the correlation is, the greater the probability is that the relationship between the categories to be evaluated is closer to this set. If all matter-elements have been evaluated, then the diagnostic system ends.

**Experimental results**

This study divides the generators into four types: normal generators, carbon brush faults, three-phase unbalance, and insulation degradation. Each type of voltage and current signal takes 30 cycles and data in 50 μs. Therefore, the total data points of each phase are 10,000, and the three-phase voltages and currents have a total of 60,000 data points. The huge amount of data is then divided into 50 groups and processed through the Chaos Theory to obtain the chaotic eye coordinate value of each type. With four types, 200 chaotic scatter plots are obtained; each has two chaotic eyes (four coordinate values), and the total is 800 eigenvalues. Next, the coordinate values are imported into the extension algorithm in the form of eigenvalues for correlation calculation and diagnosis. The measured original signal and chaotic scatter diagram for each generator type and the final extension diagnosis identification result are introduced below.

**Three-phase synchronous generator – Normal**

In this study, the measured three-phase voltage of the synchronous generator is stepped down from 0 V–220 V to 0 V–6 V (AC) by the transformer conversion circuit; the Hall components are used to extract the current signal, and the measured current signal of each phase is converted into a 1 V–10 V voltage signal. Figure 4 shows the

![Figure 4. Voltage waveform for the normal three-phase synchronous generator.](image)
three-phase voltage waveforms of a three-phase synchronous generator under normal conditions. Figure 5 shows the voltage waveform output from the Hall components.

By operating the extracted electrical signals of the generators through the Chaos Theory, with the main system as the three-phase voltage and servant system as the three-phase currents, the chaotic error scatters diagram and the chaotic eye coordinates are obtained. Figure 6 shows the chaotic error scatter diagram and the chaotic eye for a normal three-phase synchronous generator.

**Three-phase synchronous generator – Carbon brush fault**

For the measurement of carbon brush faults, the three-phase balance load of 1 kΩ is first put into use, and then the synchronous motor of the carbon brush fault is driven by the prime mover. Because the DC voltage cannot be excited, the generated voltage cannot reach the rated voltage of 220 V (about 190 V or so), and after the load is applied, it is further reduced to 180 V. After the conversion and measurement of the circuit, it is 5 V, as shown in Figure 7.

Figure 8 shows the voltage waveform converted by the Hall components. Compared with the voltage-to-voltage output value of the normal generator in Figure 5, the measured value on the oscilloscope obviously drops from 2.2 V to about 1.8 V.

After the measured waveform data are combined into a database and then operated through the proposed method, the chaotic error scatter diagram and the chaotic eye coordinates are obtained. Figure 9 shows carbon brush fault of the chaotic error scatter diagram and chaotic eye coordinates for the three-phase synchronous generator.

**Three-phase synchronous generator – Three-phase load unbalance**

In the case of three-phase load balancing, the winding resistance, leakage reactance, and excitation impedance values of each phase of the synchronous generator are the same. However, when the three-phase load is unbalanced, the voltage and current of each phase are not equal, as shown in Figure 10.

---

**Figure 5.** Current-to-voltage waveform for the normal three-phase synchronous generator.

**Figure 6.** Chaotic error scatter diagram and chaotic eye coordinates for the normal three-phase synchronous generator.
In a normal operation condition, there is only a positive sequence current inside the generator. Since the generated magnetic field is in the same direction as the rotor, no induced current is generated in the rotor. When operating in an asymmetric three-phase load condition, in addition to the positive sequence current, the internal stator winding also generates a negative sequence current, which causes the rotor to generate additional losses and heat; the rotor parts may be damaged when the problem gets more serious. For the three-phase unbalanced generators studied in this paper, under the same load of 1 kΩ, the voltage converted by each phase current is not balanced, in which the extracted current of the T phase is only 1.7 V compared with the R and S phases. Figure 11 shows the current-to-voltage waveform of the three-phase unbalanced power generation.

**Figure 7.** Voltage waveform for the carbon brush fault synchronous generator.

**Figure 8.** Carbon brush fault of the current-to-voltage waveform for the three-phase synchronous generator.

**Figure 9.** Carbon brush faults of voltage minus the current chaotic error scatter diagram and chaotic eye for the three-phase synchronous generator.

In a normal operation condition, there is only a positive sequence current inside the generator. Since the generated magnetic field is in the same direction as the rotor, no induced current is generated in the rotor. When operating in an asymmetric three-phase load condition, in addition to the positive sequence current, the internal stator winding also generates a negative sequence current, which causes the rotor to generate additional losses and heat; the rotor parts may be damaged when the problem gets more serious. For the three-phase unbalanced generators studied in this paper, under the same load of 1 kΩ, the voltage converted by each phase current is not balanced, in which the extracted current of the T phase is only 1.7 V compared with the R and S phases. Figure 11 shows the current-to-voltage waveform of the three-phase unbalanced power generation.
Adopting the same analytical procedures and operating the measured voltage and current data through the Chaos Theory, the chaotic error scatter diagram and chaotic eye coordinates are obtained, as shown in Figure 12.

Three-phase synchronous generator – Insulation degradation

Insulation deterioration leads to overvoltage, which is also one of the main causes of electrical equipment fault. With the actual measured three-phase synchronous generator in this study, the insulation value of the stator winding to the shell is about 18 MΩ, compared with the stator winding insulation resistance of the normal three-
phase synchronous generator (approximately 120 MΩ) being much smaller. The short circuit and signal interference caused by the deterioration of insulation on the stator winding coil of the generator makes it unable to reach the rated voltage. In addition, the leakage current caused by the insulation deterioration of the stator windings also causes the phase voltage to decay due to noise. With the measured signal of the three-phase synchronous generator, which is deteriorated by the insulation and operated through the Chao Theory, the chaotic error scatter diagram and the chaotic eye coordinates are obtained, as shown in Figure 13.

Extension fault diagnosis results of three-phase synchronous generator

This study adopts the chaotic eye coordinates obtained through the Chaos Theory as the eigenvalues of the identification system. There is a total of 200 chaotic eye coordinate values for the four fault types, as shown in Figure 14. The coordinate values are displayed in various combinations. If the Y coordinate values of 200 chaotic eyes are taken out and integrated into new eigenvalues, then the amount of data points drops to 100, and the chaotic eye scatter diagrams, as shown in Figure 15, are generated. It can be observed that the eigenvalues of all kinds of faults are too similar and cannot be clearly classified. Similarly, if the X coordinate values of 200 chaotic
eyes are taken out and integrated into new eigenvalues, then a chaotic eye scatter diagram, as shown in Figure 16, can be generated, since the eigenvalues of each fault type have bigger differences. Therefore, this study uses 100 chaotic eye coordinate eigenvalues to establish the extension matter-element model and applies weight coefficients (weights set to 0.2 and 0.8) to determine the weight percentage of each feature to the object. The correlation degree of every eigenvalue of the generator is measured by the normalized correlation function to finally identify its fault type.

From the identification result of the extension fault diagnosis shown in Table 1, it can be observed that the identification accuracy of the proposed method in this study reaches 100%. After adding random interference noise of ±10% to ±30%, as shown in Table 1, when the data error reaches ±30%, the accuracy of identification effect is still over 50%.

This study is also compared with the neural networks of other architectures to identify eigenvalue data with MATLAB Neural Network Toolbox, as shown in Table 2. In the same input and output for two eigenvalues and only for the fine-tuning testing of hidden layer architecture settings, 2, 3, and 10 hidden layers were, respectively, identified, with overall identification rates of 67%, 74%, and 98%. The proposed extension method has the highest recognition rate (100%) and the ranking is number 1 (the bold and underline) as shown in Table 2.
Conclusion
This study measured and retrieved the electrical signals of the generator by an oscilloscope through a hardware measurement circuit and generated a dynamic error scatter diagram through the Chaos Theory. The chaotic eye is used as the eigenvalue and finally identified by the extension diagnosis algorithm. The fault type of the three-phase synchronous generator is then diagnosed. Consequently, the proposed method not only reduces the huge data and extracts a representative eigenvalue of fault type, to which the fault diagnosis identification rate is as high as 100%, but also performs better than 98% of backpropagation neural networks. Even after adding ±10%–±30% random noise interference, the identification accuracy rate still reaches over 50%.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD
Shiue Der Lu http://orcid.org/0000-0002-0273-3916

References
1. Boulgouris NV, Konstantinos NP, Tzanakou, et al. Theory, methods and applications. Hoboken, NJ: Wiley-IEEE, 2009.
2. Mohamed Salah, Khmais Bacha, Abdelkader Chaari, et al. Brushless three-phase synchronous generator under rotating diode failure conditions. IEEE Trans Energy Convers 2014; 59: 594–601.
3. Qiang XU. Method of accurate indirect measure of power angle of waste heat generator. J Ind Sci Technol 2012; 6: 477–479.
4. Nadarajan S, Panda SK, Bhangu B, et al. Online model-based condition monitoring for brushless wound-field synchronous generator to detect and diagnose stator windings turn-to-turn shorts using extended Kalman filter. IEEE Trans Ind Electron 2016; 63: 3228–3241.
5. Quyessaad H, Gulski E and Lefebvre D. Doubly fed induction generator fault diagnosis using unknown input Takagi–Sugeno observer. In: IEEE conference on control, decision and information technologies (CoDIT), Hammamet, Tunisia, May 2013, pp.530–535.
6. Gau ZX and Xiao YJ. A study of ontology-based fault detection and diagnostic system for wind turbine. NTU Institutional Repository, 2010, pp.11–16.
7. Ernani MZ and Azirani AA. A method based on Analytical Hierarchy Process for generator fault diagnosis. IEEE Int Conf Solid Dielectr 2010; 2: 1–4.
8. Hua L, Zhanfeng L and Zhao W. Time frequency distribution for vibration signal analysis with application to turbo-generator fault diagnosis. In: Chinese Control and Decision Conference, Guilin China, June 2009, pp.5492–5495.
9. Ortega J, Bigun J and Reynolds D. Authentication gets personal with biometrics. *IEEE Signal Process Mag* 2004; 21: 50–62.
10. Tian J and Peng Y. Research of the Matlab application in the finger print identification system. *Image Anal Signal Process* 2012; 95: 11–15
11. Huang CH, Lin CH and Kuo CL. Chaos synchronization-based detector for power-quality disturbances classification in a power system. *IEEE Trans Power Delivery* 2010; 26: 944–953.
12. Yau HT and Wang MH. Chaotic eye-based fault forecasting method for wind power systems. *IET Renewable Power Gener* 2015; 9: 593–599.
13. Wang MH, Chung YK and Sung WT. The fault diagnosis of analog circuits based on extension theory. *Emerging Intell Comput Technol Appl* 2009; 5754: 735–744.