A Method to Analyze Power System Quality Disturbing Signal Based on Recurrence Quantification Analysis

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Abstract

Recurrence plot and recurrence quantification analysis (RQA) are introduced in the research of nonstationary power disturbance signal process in this thesis. Through analyzing recurrence plot of power quality disturbance signal, the recurrence phenomena are observed within different patterns of PDS internal dynamic mechanism. The recurrence characteristics are shown by RQA parameters quantitatively. With the various parameters taken through RQA, the different power disturbance patterns are differentiated. For PDS end point inspection, signal recurrence level is the characteristic parameter which is used for measuring the recurrence frequency of vector points and the aggregation level of the tracks in system phase space. Based upon this parameter, the differences of power disturbance dynamic characteristics are analyzed, and the PDS end points are also inspected. The result of simulation experiments shows that the identification and positioning of various transient disturbance signals

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Keyword: Recursive map; Phase-space reconstruction; Power quality; Quantitative recurrence analysis

1. Introduction

With the fast development of economy and society, power system has been seriously polluted by a great mount of concessional and nonlinear devices. Some problems presented and influenced power quality, such as voltage wave distortion, voltage fluctuation and flickering, voltage deviation, frequency
deviation, tri-phase imbalance, etc. Many researchers applied the sensitive property of wavelet upon abrupt changes into the inspection of power quality [1-3].

Recurrence plot and recurrence quantification analysis (RQA) [4] are developed in rapid way after they were announced. As simple analysis tools of nonlinear time sequence, they are applied in sampling signal analysis of physical phenomenon and physiological mechanism: the analysis of neuron signal; the analysis of attitude fluctuation; electrocardio variation; respiratory frequency; the end point inspection of sound and voice signal; insulator leakage current measurement [5-10]. It is avoided that the restriction of sequence length and steady state approximation upon regular nonlinear analysis.

2. Recurrence plot and recursive quantitative analysis

Usually, chaotic phenomenon is periodic, gradual, self-similar and ordered. Some certain system can generate inner randomness, but this is not simple randomness and contingency. Chaos is not simply unordered. It has no definite period and is not in symmetry, but it contains ordered structures with abundant inner levels, deep structures and orders. All of these characteristics can be displayed in some way under controlled condition.

2.1. Restructured phase space

The phase space restructure theory of Takens: choose proper embedding dimension m and latency time τ; take one dimension of nonlinear time sequence \{x_j\}; select the embedding dimension to prop up a embedding space, and choose numbers from time sequence \{x_j\} in gap time; put the numbers as component to construct a batch of m dimension vector \(y_j = (x_j, x_{j+t}, x_{j+2t}, ..., x_{j+(m+1)t})\), \(i = 1, 2, ...,\), in which \(m > 2D+1\), D as number of attractor dimensions; all these \\{x_i, i=1, 2, ...,N\} with time marks compose the m dimension phase space track of whole system.

2.2. Recurrence plot

Recurrence plot is a method of visualizing the recursive state in phase space. Recurrence plot method means to extract time sequence from system and is in order to reproduce the recursive behaviour of system dynamics. According to the phase space restructure theory of Takens, in the m dimension space, take the points there as column and row to make up a \(N \times N\) recursive matrix graph. Every node can be described with the distance between relevant vector points on column and row. The formula as below:

\[
R_{i,j} = \theta(\epsilon - \|x_i - x_j\|), i, j = 1, 2...N
\]  

(1)

In the formula, \(\epsilon\) is predetermined threshold constant, as critical distance. Symbol \(\|\|\) refers to Euclidean norm of vector. When \(R_{i,j}\) equals to 1, it will be shown as a black dot at \((i, j)\) on recurrence plot; when \(R_{i,j}\) is 0, there will be a white dot. In this way, recurrence plot shows a 2-dimension mapping of the track relationship in a m dimension phase space. For the choosing of neighbourhood radius, empirical formula is used in practice. With the estimation of original data, 0.4 to 0.5 times of standard deviation of original data will be correct. The research of recurrence plot includes macro mode and micro mode: Macro mode is to observe the attributes from overall them.

Fig. 1 is a recurrence plot of typical sinusoidal signal sequence, Lorenz formula x component in chaotic system and random noise sequence. In Fig. 1, the line patterns of periodic signal recurrence plot are in diagonal way, and show the recursive structure in periodic way. The random signal recurrence plot in Fig. 1 (c) contains isolated random dot scope which means that the isolating state of system cannot be last for a certain period and in strong randomness. However, Fig. 1 (b) is recurrence plot of chaotic
sequence, in which there are not only the patterns developed in diagonal direction, but also some isolated dots.

![Fig. 1 Typical recurrence plot](image)

### 2.3. Recurrence quantification analysis

RQA consists of five quantifiable factors: reconstruction rate, determinacy, the maximum length of diagonal line, entropy and recurrence tendency. For acquiring more detailed information from recurrence plot, some scholars introduced diagonal average length, degree of ramification, lamellar level, the maximum length of horizontal line, etc. There are four factors used in this paper: recurrence rate (RR), also reconstruction rate, refers to the percentage of recursive dot in recurrence plot within specified discriminate distance; determinacy (DET), the percentage of recursive point which located on the 45° diagonal.; entropy (ENT), the Shanon entropy of the 45° diagonal length distribution; entropy is applied for measuring the complexity of system: the greater the entropy, the system will be more complex; recurrence tendency (RT), the parameter for measuring the stability of system. It is the recurrence changing rate from main diagonal to corner on recurrence plot.

In the power quality disturbance analysis, the parameter, which can represent the disturbing signal characteristic and starting point, is reconstruction rate. Generally, higher reconstruction rate means stronger embedding effect in periodic process. Since the data in complex nonlinear sequence are random, the reconstruction of every part will definitely be different. If they are shown in power quality disturbance signal, the reconstruction different from undisturbing phase will present at the start and end of the disturbing process. In the content above, disturbance type and persisting period are classified, and the disturbing signal is positioned. Reconstruction rate is applied in all these processes.

### 3. Simulation and application

In experiment, Matlab is used as the software for disturbance signal simulating. Then, the optimal latency time $\tau$ is achieved through mutual information method; embedding dimensionality $m$ is acquired by false nearest neighbour field method. With using the phase space reconstruction method, recurrence plot is drawn out. For discriminating the type of disturbing signal, recurrence plot are drafted. The starting point of disturbance is found in recurrence quantification analysis. The tools of Matlab and RQA software [11] are combined to analyze the characteristics of disturbing signal.

#### 3.1. Signal simulation

Six kinds of common disturbance signal used in experiment are voltage sags, voltage swell, voltage break, transient oscillation, voltage peak and transient harmonic. The sampling frequency of the disturbance signals is 6400HZ; voltage frequency is 50HZ; waveform data samples on 10 cycles for each signal. Fig. 2 is the oscillogram of normal signal and six disturbance signal. Obvious starting points are shown in six transient waveforms. Voltage break, voltage swell and sag are all persisted five cycles;
transient oscillation is about one cycle; voltage peak is presented in five cycles, and in each cycle, persisting time of it is transient; the continuing time of transient harmonic is about one and a half cycle.

3.2. Recurrence plot

Different disturbance signals have distinct chaotic characteristics because of the various starting points and persisting times. Thus, there are dissimilar embedding dimensionality $m$ and latency time $\tau$. After trials, the neighbourhood radius is chosen as 1.2. Embedding dimensionality and latency time are listed in Table 1. Phase space is reconstructed with using embedding dimensionality $m$ and latency time $\tau$. Fig. 3 is the diagram of reconstructed phase space. Different disturbances are in correspondence with their obvious characteristics.

![Fig. 3: Recurrence plot of various disturbance signals](image)

In the data form calculation, the major changes are shown in embedding dimensionality, when transient oscillation and transient harmonic are in contrast with other four kinds of signal. Fig. 3 contains the recurrence plot of normal signal, voltage sags, voltage swell, voltage break, voltage peak, Transient Oscillation, Transient Harmonic after phase space reconstructed.

| Disturbance signal     | Embedding dimensionality ($m$) | Latency time ($\tau$) |
|------------------------|-------------------------------|-----------------------|
| Voltage Break          | 2                             | 3                     |
| Voltage Swell          | 2                             | 7                     |
| Voltage Sag            | 2                             | 5                     |
| Transient Oscillation  | 4                             | 6                     |
| Voltage Peak           | 4                             | 2                     |
| Transient Harmonic     | 4                             | 8                     |

In the experiment, the obvious characteristics are found that these six disturbance signals can be clearly differentiated. Those dots or segments are parallel; the distances between any neighbouring pair of them are nearly the same value. Contrasting with the waveform diagram of six signals, those distances represents the quasi-periodic property of the disturbances. The time gap of those distances means the fundamental frequency changes. In the experiment, the obvious characteristics are found that these six
disturbance signals can be clearly differentiated. Those dots or segments are parallel; the distances between any neighbouring pair of them are nearly the same value. Contrasting with the waveform diagram of six signals, those distances represents the quasi-periodic property of the disturbances. The time gap of those distances means the fundamental frequency changes. Furthermore, the diagonals with equal distance have regular local structure. The interval between a point on recurrence plot and the neighbouring point on the direction of coordinates axis is the time interval between one pair of phase points on signal graph. This interval is just a cycle. Therefore, the number of blank strip along coordinate’s axes equals to the cycle number of time signal.

In fact, there are two or more signals appearing at the same moment in the power quality disturbance in power grid. So the chaotic characteristics of single signal can be applied in the signal identification of different disturbance signals. Simulations can be conducted through this way, which is for the signals of transient harmonic and voltage swell appearing contemporarily. Fig.3 (b) is the simulation result. Recurrence plot in Fig.3 (b) have the characteristics of both the transient harmonic and voltage swell. This is similar to the recurrence plot. Therefore, the identification upon the combined signal of multi-disturbances can apply this method.

In recurrence plot, six disturbance signals can be sorted into two groups: one includes voltage break, voltage swell, voltage sag, voltage peak, four relatively simple signals; the other consists of transient oscillation and transient harmonic, which are more complex signals.

The parameters from recurrence quantification analysis can be taken as the evidences for signal identifying. Especially using the different parameters of single disturbance signal, the identification result will be more accurate. The parameters are listed in Table 2. In the table, some clear differences of signals can be found from average value, reconstruction rate, determinacy, maximum length of diagonal, entropy. The average values of voltage sag and swell are the same, because of the similarity of the disturbance characteristics of these signals. Hence, the parameters from RQA can be taken as the characteristic parameters for subsequent identification and classification.

![Recurrence plots of seven power quality disturbance signals](image1)

![Oscillogram and recurrence plot of combined disturbance signal](image2)

**3.3. Identification of power quality disturbance signal**

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Table 2: Recurrence quantification analysis parameters of various disturbance signals. RR is the recurrence rate; DET is the determinacy; RT is the recurrence tendency; ENT is the entropy

| Disturbance Signal  | Voltage Break | Voltage Swell | Voltage Sag | Transient Oscillation | Voltage Peak | Transient Harmonic |
|---------------------|---------------|---------------|-------------|------------------------|--------------|--------------------|
| RR (%)              | 91.551        | 53.440        | 82.151      | 44.308                 | 65.212       | 17.510             |
| DET (%)             | 99.860        | 99.547        | 99.782      | 88.512                 | 98.541       | 99.339             |
| RT (%)              | 99.973        | 99.797        | 99.909      | 96.403                 | 99.608       | 98.524             |
| Entropy             | 7.52          | 5.195         | 6.169       | 5.131                  | 4.923        | 6.889              |

3.4. Positioning of power quality disturbance signal

After chosen reconstruction rate parameters and conducted RQA on the phase space reconstructed signals, some changes can be found: in disturbance persisting period, reconstruction rate presents in stationary or circular style, which is different from the RR of normal signal. Some inflection points are there after using this analysis method and reconstruction rate curve graph. These inflection points are the start or end points of disturbance. Fig. 5 is the reconstruction rate curve graph: 120 dots as an interval, the coordinates of dots are the location of cycle interval points, but the start and end points are cannot be exactly determined.

From the curve graph Fig. 5, it can be seen that the reconstruction rates do not have various changes. In order to determine the sampling point where the signal will emerge, the reconstruction rate of different intervals are calculated for knowing that the RR of start or end point is quite different from previous time point. Through this way, the start and point of disturbance signal can be positioned. For voltage break, if this method applied, 120 dots will be taken as an interval: firstly, after the interval of 120 dots, the 120th dot is the start point of next interval, and an RR is calculated; then, a interval of 120 dots again, the 121st dot is the start point of next interval, and RR is calculated; here, the 241st dot can be decided as the starting point of disturbance by observing the RR changing status; after this, in the next interval of 120 dots, the 119th dots is the starting point of the following interval, and RR is calculated; the end point of disturbance situates between the 834th and 841st sampling dot. The sampling error does not exceed five sampling dots. The RRs of the critical intervals are listed in Table 3.

At the fifth column, the start point of disturbance can be determined: the status is normal between the 121st and 240th dot, and the disturbance starts at the 241st dot; when the interval started at 121st dot, the sequence between the 122nd and 242nd dot changed, and the disturbance starts at the 241st dot. The end point can be found in this way, and it will be between the 834th and 841st dot. The practical start and end point of simulation are the 241st and 840th dot. This positioning method can be applied to other disturbance signal, but there are some errors (maximum error ≤ 5 dots) for the determination upon end point.
Table 3  Reconstruction rate of various intervals

| Intervals  | 1-120 | 121-240 | 241-360 |
|------------|-------|---------|---------|
| 120 RR     | 65.322| 65.322  | 100.000 |
| 121 RR     | 65.322| 65.420  | 100.000 |

4. Conclusion

The recurrence plots demonstrate that recurrence phenomenon of power disturbance signal inner dynamic mechanism within different modes. Recurrence quantification parameters present the recurrence characteristics of power disturbance signal, with which various power disturbance modes can be differentiated. The reconstruction rate of recurrence analysis can be used for positioning the start and end point of disturbance.

From the simulation results, it can be found that the topological structure and quantitative index of recurrence plot can represent the changes of power disturbance modes, and reveal the nonlinear characteristics and development of power disturbance signal. The efficiency and accuracy of power disturbance modes identification and terminal inspection are raised in the process of simulation. Recurrence quantification analysis is a novel and direct inspection method of power disturbance mode inspection. It is also the basis of subsequent research upon power quality disturbance signal and the overlapping of various disturbance signals.

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