Fault Correspondence Analysis in Complex Electric Power Systems

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***Abstract*—Wide area measurement system (WAMS) mainly serves for the requirement of time synchronization in complex electric power systems. The analysis and control of power system mostly depends on the measurement of state variables, and WAMS provides the basis for dynamic monitoring of power system by these measurements, which can also satisfy the demands of observable, controllable, real-time analysis and decision, self-adaptive etc. requested by smart grid. In this paper, based on the principles of fault correspondence analysis, by calculating row characteristic which represents nodal electrical information and column characteristic which represents acquisition time information, we will conduct intensive research on fault detection. The research results indicate that the fault location is determined by the first dimensional variable, and the occurrence time of fault is determined by the second dimensional variable. The research in this paper will contribute to the development of future smart grid.**

***Index Terms*—synchronized phasor measurement unit, PMU, backup protection, smart grid, fault correspondence analysis, noise.**

I. Introduction

Smart grid is the development trend of future power network, it has many excellent characteristics, mainly include self-healing, safety, compatibility, high efficiency, interaction, high quality, etc. Smart grid will provide ideal solving approach for the secure and stable operation of complex large power grid, the integration of new energy, the management of demand side [1-3], and so on. In the same reference clock framework, Wide Area Measurement System (WAMS) based on Synchronized Phasor Measurement Unit (PMU) can capture each point's real-time steady-state and dynamic information of large-scale interconnected electric power system [4, 5]. WAMS is the further extension of traditional Supervisory Control and Data Acquisition system (SCADA), and it has created favorable conditions for the safety monitoring and controlling of power system. PMU plays an instrumental role in power flow calculation, state estimation of power system and the prediction of system transient stability [6-9]. And it will also provide a strong hardware support for the development of future smart grid.

As an important auxiliary system which can improve the operation safety of power system, WAMS will become an important part of future smart grid. The reliability of WAMS will also significantly impact on the secure and stable operation level of power system [10-12]. With the increasing complexity of contemporary large power network structure, the setting coordination principles of traditional backup protection based on local information quantity have been greatly affected by system operation mode, and it is difficult to meet the requirement of current relay protection. The decreasing of backup protection sensitivity, even the mismatch of protection will bring great risk to power system security [13-17]. So rapid and accurate fault analysis is always one of the most essential problem of wide area backup protection system.

In the research of fault detection in wide power grids, the experts and scholars on electrical and computer engineering have investigated many conventional detection methods, mainly include Bayesian network, genetic algorithm, artificial neural network, Petri net, expert system, fuzzy set theory, and so on. The advance of WAMS system will contribute to solve many complex problems in electric power system, such as state estimation, power angle stability, voltage stability, frequency stability, damping control, separation control, etc. And it will also provide a new important data source and development direction for fault detection in power grids.

In the research of complex electric power systems, we have obtained great achievements. In paper [18], the bifurcation theory has been introduced into complex nonlinear systems, we have adopted a novel approach to identify faults in electric power systems. Large numbers of complicated and high-precision calculations indicate that each fault in an electric circuit system must correspond to one or more bifurcation locations, which will provide a bifurcation criterion of faults in complex electric power systems. In paper [19], the research mainly focused on the centralized decision and distributed implementation of wide area backup protection system in large-scale power grid. According to different kinds of complex system failures, a novel fault factor analysis scheme which can realize rapid, accurate and effective fault detection have been put forward, and many simulations have also verified the effectiveness of fault factor analysis. In paper [20], based on fuzzy cluster analysis theory and the principle of minimum expected cost of misclassification, a comprehensive detection and isolation system of fault in complex power system have been explored. And the comprehensive fault detection and isolation system will provide guarantee for the safety and stable operation of electrical power and energy system.

The paper is organized as follows. In Section 2, the

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principles of fault correspondence analysis are introduced, and the algorithm flow of fault correspondence analysis will also be explained in details. In Section 3, considered the noise interference in the process of PMU information acquisition, the fault correspondence analysis under white Gaussian noise background is discussed carefully, and many interesting results will be obtained. Finally, the paper is concluded in Section 4.

II. Principles of Fault Correspondence Analysis

In the research of characteristic extraction problems, the characteristic analysis according to variables and the characteristic analysis according to samples, both are able to display certain characteristics of a unit. But its comprehensive characteristic attribute tends to have higher research value. Correspondence analysis utilizes the thought of dimension reduction, and explores comprehensive characteristics of a unit by transition matrix Z of corresponding transformation [21-23].

Consider an observation data matrix with n samples of m variables,

$$X = \left(x_1 \;\; x_2 \;\; \cdots \;\; x_n\right)' = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{pmatrix} \tag{1}$$

wherein $x_{ij} \ge 0 \; (i = 1,2,\cdots,n; \; j = 1,2,\cdots,m)$. If let

$$x_{i.} = \sum_{j=1}^{m} x_{ij}, \; x_{.j} = \sum_{i=1}^{n} x_{ij}, \; T = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \tag{2}$$

one can get a standardized probability matrix of raw data,

$$P = \frac{X}{T} = \left(p_1 \;\; p_2 \;\; \cdots \;\; p_n\right)' = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nm} \end{pmatrix} \tag{3}$$

wherein $p_{ij} = \dfrac{x_{ij}}{T}$ and $p_{i.} = \sum_{j=1}^{m} p_{ij}, \; p_{.j} = \sum_{i=1}^{n} p_{ij}$.

Further, let's define two diagonal matrices A and B, the main diagonal element of A is $p_{i.}$, and the main diagonal element of B is $p_{.j}$. Let's transform matrix P with A and B.

$$Z = A^{-\frac{1}{2}} P B^{-\frac{1}{2}} \tag{4}$$

It is one of the characteristics of correspondence analysis that the transformation method which can realize data matrix standardization. And this kind of transformation is drawn up according to the similarity measure between samples and variables.

In order to get the same matrix's loading of R analysis on the basis of variables and Q analysis on the basis of samples, we adopt weighted distance as the similarity measure,

$$D(s,t) = \sqrt{\sum_{j=1}^{m} \left(\frac{p_{sj}}{p_{s.}} - \frac{p_{tj}}{p_{t.}}\right)^2 \frac{1}{p_{.j}}} \tag{5}$$

And then, each sample can be considered the vector with the following coordinate,

$$\left(\frac{p_{i1}}{p_{i.}\sqrt{p_{.1}}}, \frac{p_{i2}}{p_{i.}\sqrt{p_{.2}}}, \cdots, \frac{p_{im}}{p_{i.}\sqrt{p_{.m}}}\right), \quad (i = 1,2,\cdots,n) \tag{6}$$

Similarly, the weighted distance between two variables is,

$$D(i,j) = \sqrt{\sum_{k=1}^{n} \left(\frac{p_{ki}}{p_{.i}\sqrt{p_{k.}}} - \frac{p_{kj}}{p_{.j}\sqrt{p_{k.}}}\right)^2} \tag{7}$$

In the course of characteristic extraction, the covariance matrix of variables in R^n sample space is,

$$\Sigma = (\sigma_{ij}) \tag{8}$$

wherein

$$\begin{aligned} \sigma_{ij} &= \sum_{k=1}^{n} p_{k.} \left(\frac{p_{ki}}{p_{k.}\sqrt{p_{.i}}} - \sqrt{p_{.i}}\right)\left(\frac{p_{kj}}{p_{k.}\sqrt{p_{.j}}} - \sqrt{p_{.j}}\right) \\ &= \sum_{k=1}^{n} \left(\frac{p_{ki} - p_{k.}p_{.i}}{\sqrt{p_{k.}p_{.i}}}\right)\left(\frac{p_{kj} - p_{k.}p_{.j}}{\sqrt{p_{k.}p_{.j}}}\right) \end{aligned} \tag{9}$$

If let $Z = (z_{ij})$, and

$$z_{ij} = \frac{p_{ij} - p_{i.}p_{.j}}{\sqrt{p_{i.}p_{.j}}} = \frac{x_{ij} - x_{i.}x_{.j}/T}{\sqrt{x_{i.}x_{.j}}} \tag{10}$$

then the covariance matrix can be expressed as,

$$\Sigma = Z'Z \tag{11}$$

In this same way one can obtain the covariance matrix of samples in R^m variable space,

$$G = ZZ' \tag{12}$$

For

$$\Sigma = U\Lambda_m U' \tag{13}$$

wherein U is the eigenvector of Σ, and Λ_m is a diagonal matrix constituted by m eigenvalues. If let λ_k be the k-th nonzero eigenvalue, and U_k be corresponding eigenvector, then

$$\Sigma U_k = \lambda_k U_k \tag{14}$$

That is,

$$Z'ZU_k = \lambda_k U_k \tag{15}$$

If the rank of Σ is r, then there are r nonzero eigenvalues at most. Left multiplication Z, one can get

$$ZZ'(ZU_k) = \lambda_k (ZU_k) \tag{16}$$

If let $V_k = ZU_k$, then

$$GV_k = \lambda_k V_k \tag{17}$$

So Σ and G have the same nonzero eigenvalues. Taking a similar approach, one can get the loading matrix of Q analysis on the basis of samples,

$$G = ZZ' = V\Lambda_n V' \\ QQ' = V\Lambda_n V' \tag{18}$$

namely

$$Q = V\Lambda_n^{1/2} = ZU\Lambda_n^{1/2} \tag{19}$$

That is to say, if the eigenvector of Σ is U, then ZU is the eigenvector of G; conversely, if the eigenvector of G is V, then $Z'V$ is the eigenvector of Σ. In this way, we can use the same factor axis to simultaneously represent variables and samples, and unify the R analysis Q and analysis. Ultimately, all of these variables and samples will be reflected on a factor plane. Based on the principles of correspondence analysis, we have put forward the following fault correspondence analysis algorithm flow, see Figure 1.

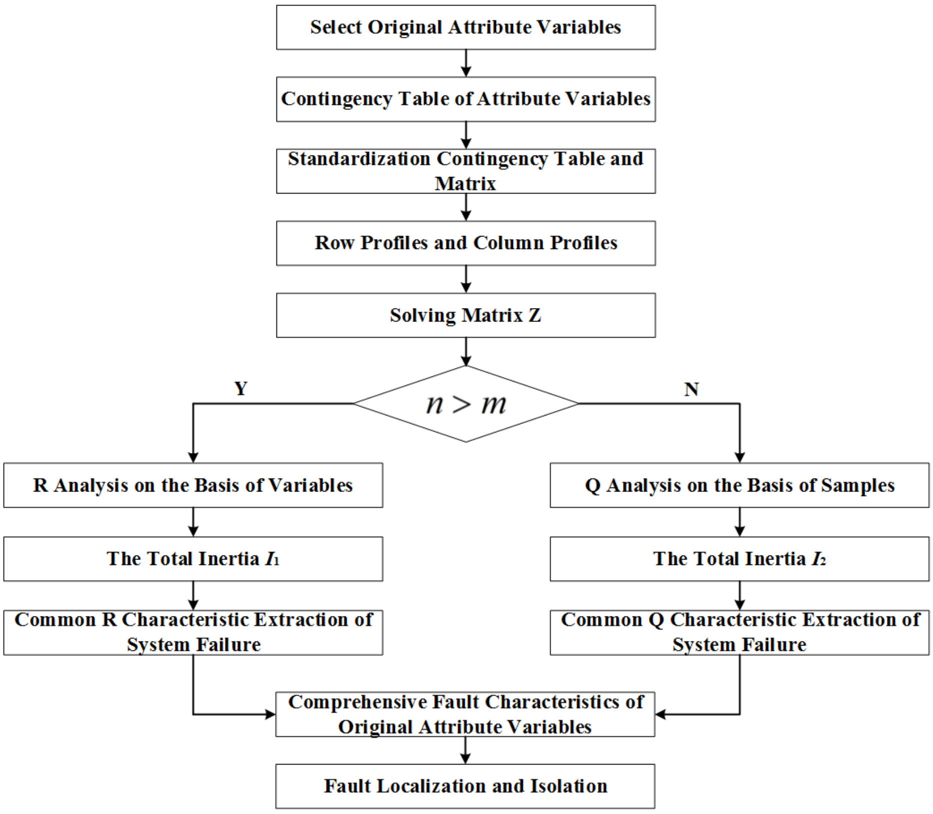

Figure 1. The algorithm flowchart of fault correspondence analysis

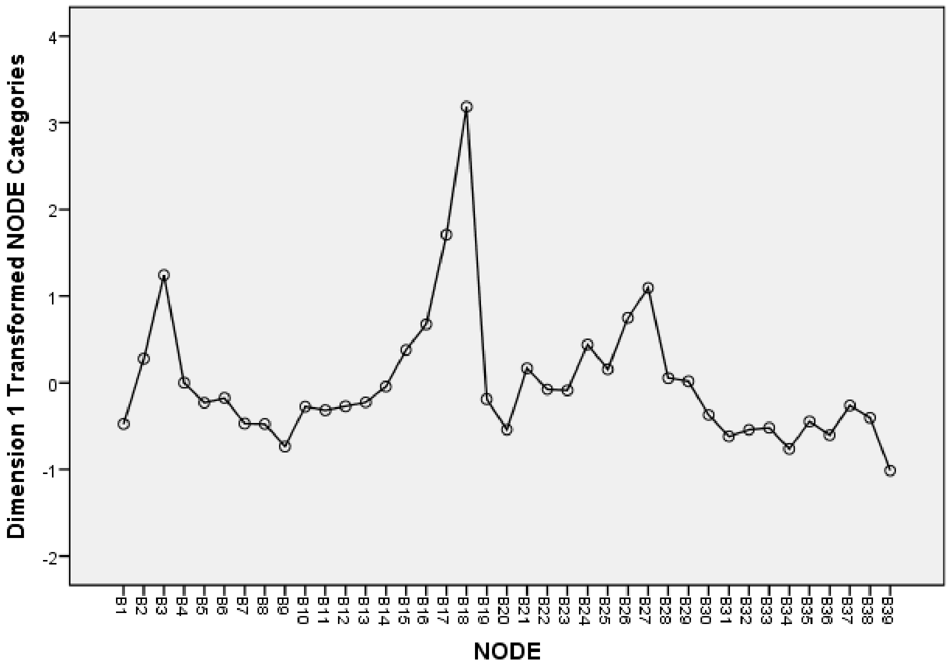

Figure 2. The transformed NODE categories on the basis of Dimension 1

III. Fault Correspondence Analysis under White Gaussian Noise Background

Within the scope of wide area electric power systems, WAMS is able to implement the real-time acquisition of large-scale interconnected power grid's dynamic information in the unified clock framework. The information data collected by PMUs will be transferred to dispatching center through high-speed communication network, and the master station system can analyze and deal with the real-time operating state of large power grid [24-26]. So, WAMS system must have very high reliability. But the signal interference in WAMS system exists everywhere, one of the most important interference source is the noise interference in the process of PMU information acquisition.

TABLE I. THE SUMMARY RESULTS OF INERTIA ANALYSIS IN UNSYMMETRICAL SHORT-CIRCUIT FAULT

Dimension	Singular Value	Inertia	Proportion of Inertia		Confidence Singular Value	
			Accounted for	Cumulative	Standard Deviation	Correlation
1	0.582	0.339	0.742	0.742	0.138	-0.074
2	0.340	0.116	0.253	0.995	0.280	*
3	0.036	0.001	0.003	0.998	*	*
4	0.033	0.001	0.002	1.000	*	*
Total	*	0.457	1.000	1.000	*	*

TABLE II. ROW ANALYSIS BASED ON NODAL ELECTRICAL INFORMATION

Node	Mass	Score in Dimension		Inertia
		1	2	
Bus 1	0.026	-0.476	0.429	0.005
Bus 2	0.026	0.277	0.398	0.003
Bus 3	0.026	1.242	-0.545	0.026
Bus 4	0.026	-0.001	1.955	0.033
Bus 5	0.026	-0.230	-0.610	0.004
Bus 6	0.026	-0.176	-0.402	0.002
Bus 7	0.026	-0.471	-0.529	0.006
Bus 8	0.026	-0.477	0.194	0.004
Bus 9	0.026	-0.735	0.049	0.008
Bus 10	0.026	-0.275	-0.046	0.001
Bus 11	0.026	-0.318	-0.444	0.003
Bus 12	0.026	-0.271	-0.519	0.004
Bus 13	0.026	-0.225	-0.736	0.006
Bus 14	0.026	-0.044	1.228	0.013
Bus 15	0.026	0.379	-0.396	0.004
Bus 16	0.026	0.675	-0.377	0.008
Bus 17	0.026	1.708	0.004	0.044
Bus 18	0.026	3.184	0.462	0.153
Bus 19	0.026	-0.190	-0.150	0.001
Bus 20	0.026	-0.541	-0.645	0.008
Bus 21	0.026	0.166	-0.254	0.001
Bus 22	0.026	-0.076	-0.112	0.000
Bus 23	0.026	-0.088	-0.066	0.000
Bus 24	0.026	0.440	0.692	0.007
Bus 25	0.026	0.155	0.469	0.002
Bus 26	0.026	0.748	-0.058	0.008
Bus 27	0.026	1.095	-0.603	0.021
Bus 28	0.026	0.055	0.148	0.000
Bus 29	0.026	0.017	-0.454	0.002
Bus 30	0.026	-0.371	-0.588	0.005
Bus 31	0.026	-0.619	0.137	0.006
Bus 32	0.026	-0.542	0.013	0.005
Bus 33	0.026	-0.520	0.221	0.005
Bus 34	0.026	-0.763	1.354	0.025
Bus 35	0.026	-0.447	-0.404	0.004
Bus 36	0.026	-0.604	-0.445	0.007
Bus 37	0.026	-0.262	-0.265	0.002
Bus 38	0.026	-0.404	0.560	0.005
Bus 39	0.026	-1.013	0.331	0.016
Active Total	1.000	*	*	0.457

According to IEEE Standard for Synchrophasors for Power Systems [27], in the research of fault correspondence analysis, we will introduce some white Gaussian noise.

In order to illustrate the detail procedure, IEEE 39 Bus system will be the major research object, and the electric diagram of IEEE 39 Bus system can refer to [19]. In the network system architecture, an unsymmetrical short-circuit fault occurred on Bus 18. Considering the influence of stochastic white Gaussian noise $N(0, 0.005^2)$, by BPA simulation, we have got the nodal negative sequence voltages at Time1, Time2, Time3, Time4 and Time5.

Based on the principles of fault correspondence analysis, one can first calculate the row profiles (represent nodal electrical information) and column profiles (represent acquisition time information), and obtain the summary results of inertia analysis, see Table I.

Much information has been provided by summary, include singular value, inertia, total inertia, proportion of inertia, and so on. In this simulation, the total inertia is 0.457, and the first dimension accounts for 74.2% of the total inertia, the second dimension accounts for 25.3% of the total inertia, and the first two dimension has accounted for 99.5% of the total inertia. So, in the course of fault characteristics extraction, we will focus on the first two dimensional variables. The summary table has also simultaneously indicated the relationship of row and column in contingency table.

According to the first dimensional variable and the second dimensional variable, one can further acquire the corresponding score of each node, see Table II. For the first dimensional variable, the score of Bus 18 is 3.184, which is the biggest among all of the first dimensional scores. Based on this, one can determine that Bus 18 is the actual fault location. In addition, fault correspondence analysis has also provided some other valuable information to help us complete the fault analysis. The transformed NODE categories on the basis of Dimension 1 is presented in Figure 2. In the categories results, Bus 18 is obviously different from other nodes, the fault characteristic is distinct.

Now let's continue to calculate the column's characteristics which represent acquisition time information, see Table III. Here we concentrate on the second dimensional variable. It is not difficult to find out that the score of Time1 based on the second dimensional variable is 1.302, which is the biggest among all of the second dimensional scores. So, one can determine that the occurrence time of fault should be at the end of Time1 or at the beginning of Time2, which is consistent with the real situation.

Finally, in accordance with the above fault correspondence analysis about the first dimensional variable and the second dimensional variable, one can aggregate these results into one figure, see Figure 3, which is also the key results of fault correspondence analysis. The fault characteristic is clearly visible. As the true fault node, Bus 18 has significant difference with other nodes, and it distributes in the scope of Time2. Consequently, the eventual conclusion is that Bus 18 is just the fault location. Therefore, based on the principles of fault correspondence analysis, we have achieved successful fault identification, and all of the results are accurate and reliable.

TABLE III. COLUMN ANALYSIS BASED ON INFORMATION ACQUISITION TIME

TIME	**Mass**	**Score in Dimension**		**Inertia**	**Contribution**				
					Point to Inertia of Dimension		**Dimension to Inertia of Point**		
		1	**2**		**1**	**2**	**1**	**2**	**Total**
Time1	0.200	-0.085	1.302	0.116	0.002	0.997	0.007	0.993	1.000
Time2	0.200	0.856	0.021	0.086	0.252	0.000	0.990	0.000	0.990
Time3	0.200	0.850	0.030	0.085	0.248	0.001	0.990	0.001	0.990
Time4	0.200	0.850	0.047	0.085	0.248	0.001	0.989	0.002	0.991
Time5	0.200	0.853	0.031	0.086	0.250	0.001	0.990	0.001	0.991
Active Total	1.000	*	*	0.457	1.000	1.000	*	*	*

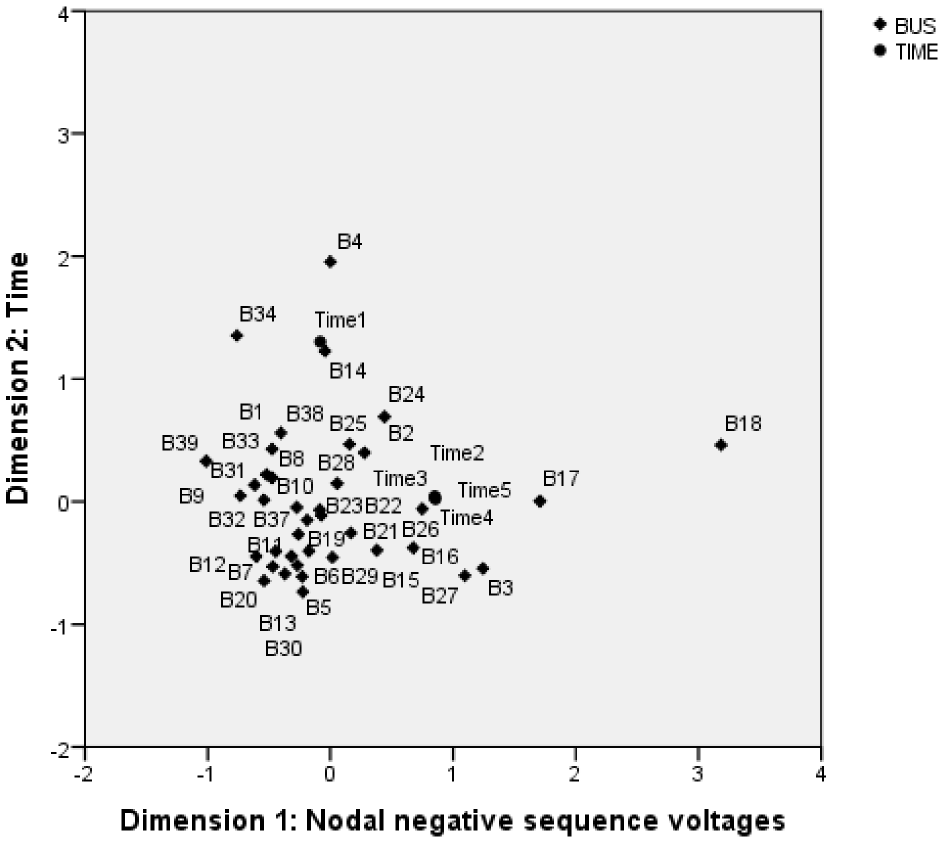

Figure 3. The row and column points symmetrical normalization results

IV. Conclusion

With the rapid development of network communication technology, the constant improvement of wide area synchronized measurement technology and digital substation technology in power system, the traditional relay protection in complex large power grid circumstances is facing difficult setting coordination. In order to safeguard the secure and stable operation of power system, the analysis method's research on rapid identifying and clearing fault is always the key problem of wide area backup protection system, which has also provided the new support for the development of smart grid.

In the research of characteristic extraction problems, correspondence analysis can be able to analyze the raw data structure by utilizing dimension reduction technology. In a succinct way, the relationship among attribute variables or different states of attribute variables will be revealed by correspondence analysis. Compared with conventional fault detection methods in power grids, fault correspondence analysis can take full advantage of the real-time information of WAMS system. By extracting the row characteristic and column characteristic respectively, fault correspondence analysis will be able to obtain desirable comprehensive fault detection results.

In this paper, we have put forward a new perspective for fault detection in complex electric power systems. Based on the principles of fault correspondence analysis, by calculating row characteristic which represents nodal electrical information and column characteristic which represents acquisition time information, we can realize accurate fault identification. The research results indicate that the fault location is determined by the first dimensional variable, and the occurrence time of fault is determined by the second dimensional variable. All of these results can be aggregated into a fault correspondence analysis diagram. The research of this paper will have significant theoretical value and engineering practical significance. And it will also contribute to the development of future smart grid.

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