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A New Power System Fast Fault Diagnosis and Analysis Approach based on WAMS

Ziguan Zhou, Xiaomin Bai, Xiaojun Li, Zaihua Li and Jing Xu

***Abstract*--A new power system fast fault diagnosis and analysis system (FFDAS) based on wide area measurement system (WAMS) was presented in this paper. Firstly, the structure of FFDAS was introduced. Then components, methods and work flows of the six agents in the FFDAS were described in detail. Finally, fast reaction, effective fault diagnosis and exact fault analysis were shown in a practical cascading failure happened in 2006.**

***Index Terms*--power system, fault diagnosis, fault analysis, WAMS, false-operation, fail-operation**

I. Introduction

WITH the development of power system which is becoming more and more complex, power systems are being operated close to their stability limits. And recently, the serious unpredictable system cascading failure may cause system wide blackouts [1], [2], which attracts the attention of researchers to the fault diagnosis and analysis of power system.

Several fault diagnosis systems have been developed and are used now. The need for the development of fault diagnosis system has been recognized since the 1960s [14]. The prevailing fault diagnosis systems are based on expert system [3], [4], artificial neural network (ANNs) [5], [6], and optimal theory [7]. The fault diagnosis systems based on fuzzy set theory [8], information theory [9], [10], and rough set theory [11] aim at settling the incomplete and uncertain information problem. A fault diagnosis based on cooperative expert system and multi-agent technology was presented in literature [12]. Paper [13] presents a fault diagnosis and analysis system based on complex event processing (CEP) technology. And a whole solution for large-scale power grid fault diagnosis and analysis system was described in paper [15].

The data source of the contemporary software tools presented in the above papers is the information of switchgears and protections from SCADA (supervisory control and data acquisition) and EMS (energy management system). Questions such as delayed transferring protections information and asynchronous time span make it difficult in fault diagnosis and analysis at high-level dispatching centre.

The fast development and wide applications of WAMS provide a new date source for large-scale interconnection power system fault diagnosis and analysis. A new approach for FFDAS was detailly presented based on WAMS in this paper.

II. STRUCTURE OF FFDAS

The architecture of FFDAS based on WAMS has three levels which is oriented to data service and developed from multi-agent technology. Figure 1 shows the three-level architecture of FFDAS. The first level is data communication. The second level is data process. The third level is data application. And the structure of the FFDAS is illustrated in figure 2.

Data Application Level	**Start Agent** **Fast Fault Location Agent** **Fast Fault Diagnosis Agent** **Fast Fault Analysis Agent**	**Application Server**
Data Process Level	**Data Process Agent**	**Data Server**
Data Communication Level	**Communication Agent**	**Communication Server**

Fig. 1. Three levels architecture of FFDAS

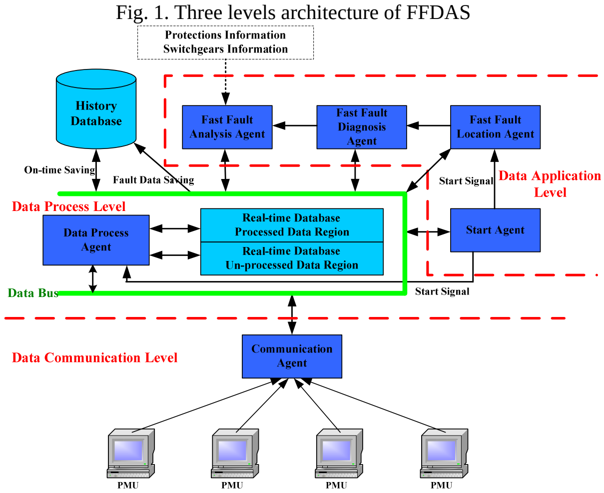

Fig. 2. Structure of FFDAS

Data communication level runs on the communication

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server. Communication agent is responsible for receiving PMU (phasor measurement unit) data according to the rule of Power Grid Real-time Dynamic Supervisory System Technical Criterion and writing them into un-processed data region of real-time database.

Data process level runs on the data server. Data process agent deals with the data and generates satisfied data which is written into processed data region of real-time database with CEP technology. These data will be supplied for other agents, and data process agent also saves fault data and other operation data into the history database based in schedule.

Data application level works on the application sever. Start agent inspects dynamic data and sends out start signal to data process agent, fast fault location agent, fast fault diagnosis agent and fast fault analysis agent. Lines collection matching the start criterion is given out as well. Fast location agent select the fault line from lines collection supplied from start agent using fast fault location method on the base of fault data of data process agent. Fast fault diagnosis agent judges fault style quickly according to the compare of standard fault character collection and real-time fault character collection generated from fault data. Fast fault analysis agent estimates false-operation and fail-operation of protection and switchgear.

Communication agent's structure is simple which is not described here. In later of this paper, data process agent, start agent, fast fault location agent, fast fault diagnosis agent and fast fault analysis agent are introduced respectively.

III. MAIN AGENT AND METHOD

A. Data Process Agent

ARCHON (Architecture for cooperative heterogeneous on line systems) structure is adopted in data process agent. Figure 3 shows the structure of data process agent.

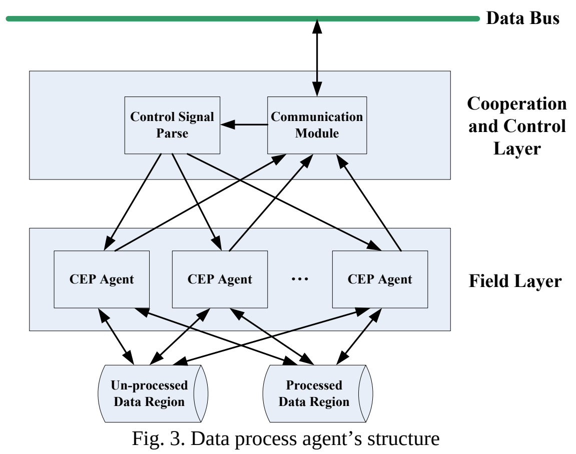

Fig. 3. Data process agent's structure

Data request signal is sent to control signal parse by communication module. And control signal is sent to corresponding CEP agent after analysing. CEP agent computes with the unprocessed data and processed data stored in the real-time database, and returns the xml data files to communication module which sending xml data files to other agent via data bus. Paper [16] introduced CEP technology and its application in power system fault diagnosis and analysis.

B. Start Agent

The key part of start agent is start criterion. Start criterion is required to send start signal sensitively and be silently in normal. There are two criterions in start agent. One is current difference start criterion, the other is three phases current sample start criterion.

Current difference start criterion

Current difference start criterion is:

$$\Delta i(n) = |i(n) - i(n-N)| - |i(n-N) - i(n-2N)| > I_D$$

$i(n)$ is current sample at n point or when nT_s. N is the number of samples for each period, $NT_s = 20ms$. I_D is start threshold value.

If a fault happened at n point, $i(n)$ is the fault current. $i(n-N)$ and $i(n-2N)$ are current at one period and two periods before the fault time n, respectively.

Start agent sends start signal when the function $\Delta i(n) > I_D$ is true triple times successively.

Three phases current sample start criterion

Three phases current is symmetric without fault, and three phases current samples are equal to three single phase current samples at the same second. The interval of the three phases is $2\pi/3$, and the virtual value is:

$$I_m{}^2 = \frac{i_b{}^2(t) - i_c(t)i_a(t)}{1 - \left(\frac{i_a + i_c}{2i_b}\right)^2} = \frac{4}{3}\left(i_b{}^2(t) - i_c(t)i_a(t)\right)$$

$$i_b{}^2(t) - i_c(t)i_a(t) = \left(\frac{\sqrt{3}}{2}I_m\right)^2 = \frac{3}{4}I_m{}^2$$

$$(i_a(t) - i_b(t))^2 + (i_b(t) - i_c(t))^2 + (i_c(t) - i_a(t))^2 = \frac{9}{2}I_m{}^2$$

I_m is phase current magnitude. i_a, i_b, i_c is A, B, C phase current samples, individually.

When three phases current is unsymmetric, the function can be expressed by positive sequence, negative sequence and zero sequence.

$$(i_a(t) - i_b(t))^2 + (i_b(t) - i_c(t))^2 + (i_c(t) - i_a(t))^2 =$$

$$9I_{1m}{}^2 + 9I_{2m}{}^2 + 9I_{1m}I_{2m}\sin(2\omega t + (\varphi_1 + \varphi_2))$$

ω is angular frequency, φ is initial phase. 1, 2, 0 represents positive sequence, negative sequence and zero sequence.

Three phases current negative sequence is lower in normal, and its angular frequency is equal to positive sequence which is determined by system angular frequency. Start criterion should select AC vector for eliminating load fluctuating and system oscillation.

Above all, three phases sample current start criterion is:

$$\Delta f(t)=\left\| f(t)-f(t-N)\right|-\left|f(t-N)-f(t-2N)\right\| >1.25I_{m\max}$$

$$f(t)=\sqrt{\frac{2}{9}\left[(i_a(t)-i_b(t))^2+(i_b(t)-i_c(t))^2+(i_c(t)-i_a(t))^2\right]}$$

where $I_{m\max}$ is the max load current in normal.

C. Fast fault location Agent

Power angle location method

Power angle location method is based on the different angle between bus voltage and line current when the fault happened in or out of lines as shown in figure 4.

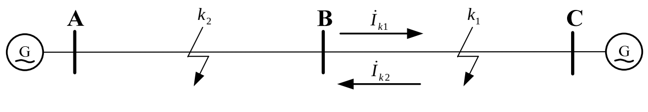

Fig. 4. Power angle location mechanism

$\dot{U}_B$ is the reference angle, and the angle between bus to line is the positive angle. When a short happened in k_1, $\dot{I}_{k1}$ is line BC's current. φ_{k1} is the angle between $\dot{U}_B$ and $\dot{I}_{k1}$. When the short happened in k_2, $\dot{I}_{k2}$ is line BC's current. φ_{k2} is the angle between $\dot{U}_B$ and $\dot{I}_{k2}$. We will get the results $-90^\circ \le \varphi_{k1} \le 90^\circ$ and $\varphi_{k2} > 90^\circ$, $\varphi_{k2} < -90^\circ$ from figure 4.

Summarily, if the angle between bus voltage and line current satisfies the function $-90^\circ \le \varphi \le 90^\circ$ at the two ends of the line, this line is the fault line.

High frequency component location method

Dispersed capacitance in the bus filters out high frequency component of the short fault current. If the third level's results contain high frequency component after separating current signal by morphologic method, this line is the fault line. If the first level's results mainly contain low frequency component after separating current signal by morphologic method, this line is not the fault line.

Structure component is chosen to right-angled triangle with height 5 and width 5 according to field experience. The results are ρ^1, ρ^2 and ρ^3. Spectrum energy I_{op} and I_{re} are start portion and brake portion, respectively.

$$I_{op}(nT_s)=\sum_{i=n-M}^{n}\left[\rho^3(iT_s)\right]^2,\quad I_{re}(nT_s)=\sum_{i=n-M}^{n}\left[\rho^1(iT_s)\right]^2$$

$$nT_s = 20ms$$

Then if $Ratio = I_{op}/I_{re} > Ratio_{set}$, this line is the fault line.

D. Fast fault diagnosis Agent

Fast fault diagnosis agent receives fault data from data process agent, and then computes the character collection. Relationship between character collections and fault styles which is shown in table Ⅰ.

TABLE Ⅰ.
RELATIONSHIP BETWEEN CHARACTER COLLECTIONS AND FAULT STYLES

Character Collection	Fault Style
A	Single-phase grounding fault
B	Two-phase grounding fault
C	Two-phase short circuit fault
D	Three-phase short circuit

Character collection's computing process is shown in appendix.

Flow chart of fast fault diagnosis agent is described in figure 5.

The probability of short fault is single-phase grounding fault, two-phase grounding fault, two-phase short circuit fault and three-phase short circuit which are sorted by priority. And we compute and match on the foundation of this sequence, which makes expected process time minimum.

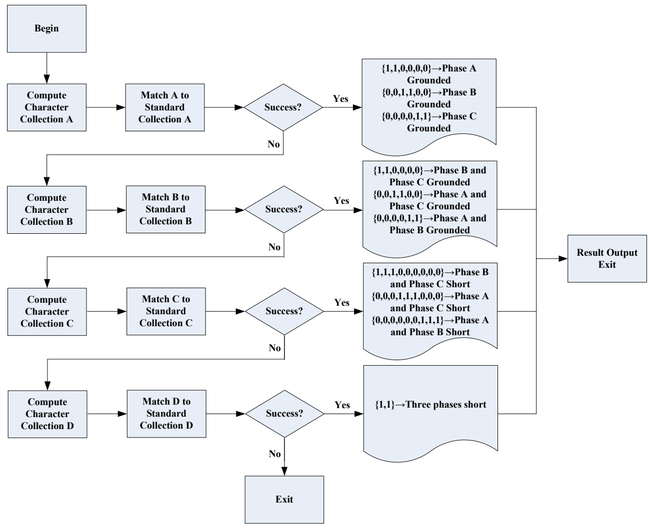

Fig. 5. Flow chart of fast fault diagnosis agent

E. Fast fault Analysis Agent

Fast fault analysis agent estimates false-operation and fail-operation of protection and switchgear. Figure 6 shows the work flow of fast fault analysis agent.

Switchgear action model evaluates whether there is a switchgear action. The module drew in dashed means that they could work when receiving protection action information. Diagnosis blind spot is solved by the ways shown in figure 7.

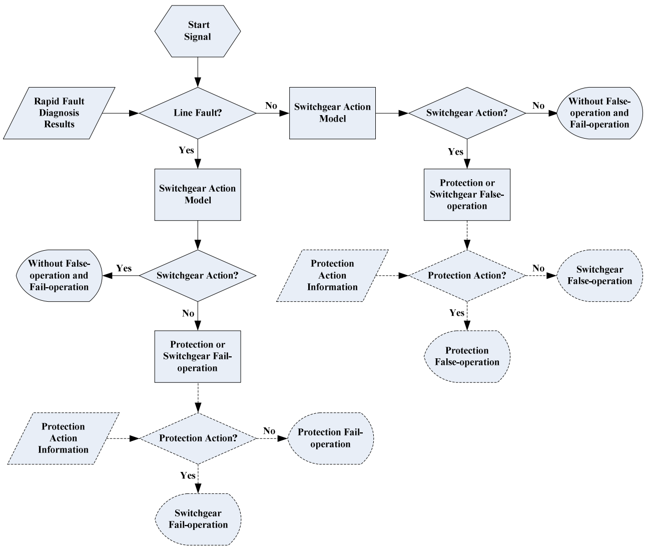

Fig. 6. Work flow of fast fault analysis agent

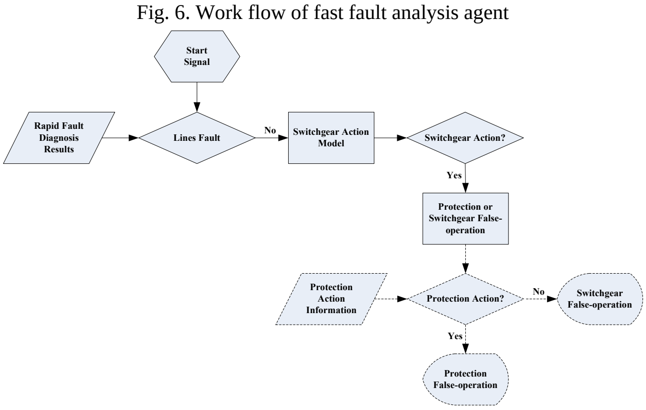

Fig. 7. Solution path of blind spot

IV. CASE ANALYSIS

There is a practical cascading failure case happened in 2006. A portion of the power grid shows in figure 8, it is used to explain how the FFDAS works. The bold lines in the figure are 500kV transmission lines. The normal lines in the figure are 220kV transmission lines. Station A's electric diagram is shown in figure 9. Before the accident happens, Bus I of Station A is outage and Breaker 5011, Breaker 5021, Breaker 5031, Breaker 5041 are all outage.

The beginning of the blackouts was 500kV line AB Ⅱ opened. The protection type was phase C current differential. Three phases opened due to unsuccessful reclosing. But this protection action was false-operation, every on-line tool and software did not judged it. This is the blind spot!

FFDAS worked as follows. Start agent could send out start signal sensitively because of the current descending quickly. Fast location agent select fault lines immediately after receiving start signal. Character collection A,B,C,D are $\{0,0,1,0,0,1\}$, $\{0,1,0,0,0,0\}$, $\{1,0,0,0,0,0,1,0,0\}$ and $\{0,0\}$. There was no short fault. Fast fault analysis agent established that this accident was false-operation of protection. The work flow of fast fault analysis agent was shown in figure 10.

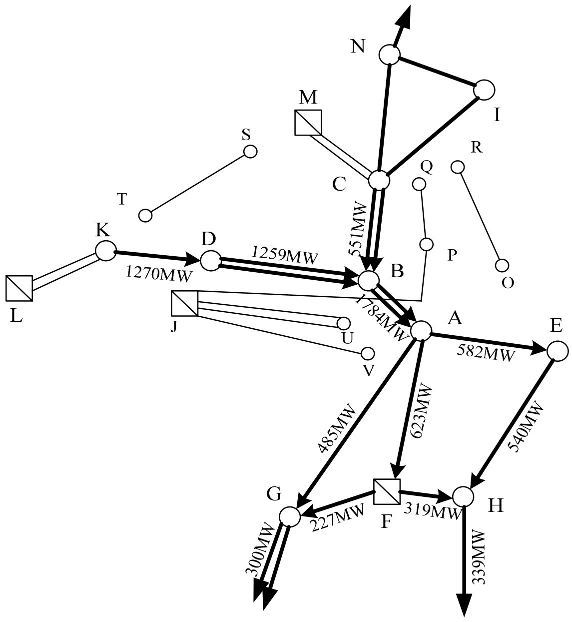

Fig. 8. Portion of the power grid in a cascading case in 2006

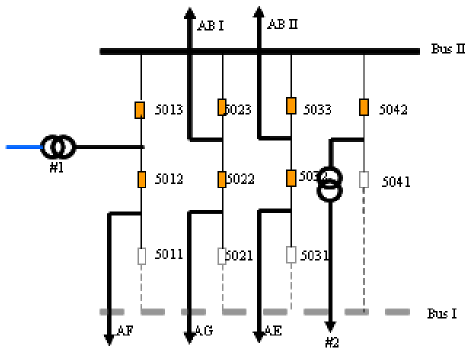

Fig. 9. Electric diagram of Station A

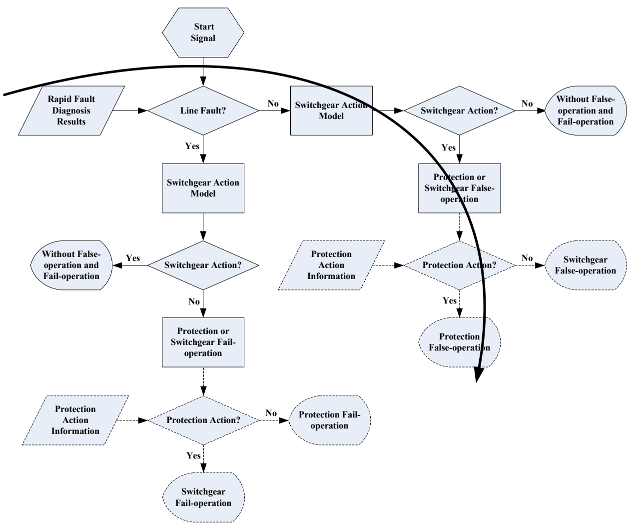

Fig. 10. False-operation analysis flow

V. CONCLUSIONS

This paper presented a new approach based on WAMS for power system fast fault diagnosis and analysis. FFDAS is more effective than other method due to the use of WAMS. FFDAS has solved a false-operation blind spot in fault diagnosis. And then FFDAS may reduce probability of cascading failures because most of primary faults of blackouts are false-operation of protections or switchgears. More attention on fault diagnosis and analysis should be given by reason of exact fault diagnosis and analysis results which are being preconditioned for other on-line tools and software.

VI. APPENDIX

Fast fault diagnosis agent receives fault data $\dot{I}_a$, $\dot{I}_b$, $\dot{I}_c$ from data process agent.

$\dot{I}_{a(1)}$, $\dot{I}_{a(2)}$, $\dot{I}_{a(0)}$ are phase A positive sequence current, negative sequence current and zero sequence current, respectively. $\dot{I}_{b(1)}, \dot{I}_{b(2)}, \dot{I}_{b(0)}$ are corresponding to phase B. $\dot{I}_{c(1)}, \dot{I}_{c(2)}, \dot{I}_{c(0)}$ to C.

Setting $a = e^{j120^\circ}$,

$\dot{I}_{a(1)} = \frac{1}{3}(\dot{I}_a + \alpha\dot{I}_b + \alpha^2\dot{I}_C)$, $\dot{I}_{a(2)} = \frac{1}{3}(\dot{I}_a + \alpha^2\dot{I}_b + \alpha\dot{I}_C)$, $\dot{I}_{a(0)} = \frac{1}{3}(\dot{I}_a + \dot{I}_b + \dot{I}_C)$.

$\dot{I}_{b(1)} = \frac{1}{3}(a^2\dot{I}_a + \dot{I}_b + a\dot{I}_c)$、$\dot{I}_{b(2)} = \frac{1}{3}(a\dot{I}_a + \dot{I}_b + a^2\dot{I}_c)$、$\dot{I}_{b(0)} = \frac{1}{3}(\dot{I}_a + \dot{I}_b + \dot{I}_c)$

$\dot{I}_{c(1)} = \frac{1}{3}(a\dot{I}_a + a^2\dot{I}_b + \dot{I}_c)$、$\dot{I}_{c(2)} = \frac{1}{3}(a^2\dot{I}_a + a\dot{I}_b + \dot{I}_c)$、$\dot{I}_{c(0)} = \frac{1}{3}(\dot{I}_a + \dot{I}_b + \dot{I}_c)$

Character collection $A = \{A_0, A_1, ..., A_5\}$, where elements in collection A are binary value. As shown in table 2, if the inequation is true and the corresponding element is 1.

TABLE 2

CHARACTER COLLECTION A

A_0	$3-\varepsilon < \frac{\lvert\dot{I}_{a(0)}\rvert}{\lvert\dot{I}_{a(1)}\rvert} + \frac{\lvert\dot{I}_{a(0)}\rvert}{\lvert\dot{I}_{a(2)}\rvert} + \frac{\lvert\dot{I}_{a(1)}\rvert}{\lvert\dot{I}_{a(2)}\rvert} < 3+\varepsilon$
A_1	$3-\varepsilon < \frac{\arg\dot{I}_{a(0)}}{\arg\dot{I}_{a(1)}} + \frac{\arg\dot{I}_{a(0)}}{\arg\dot{I}_{a(2)}} + \frac{\arg\dot{I}_{a(1)}}{\arg\dot{I}_{a(2)}} < 3+\varepsilon$
A_2	$3-\varepsilon < \frac{\lvert\dot{I}_{b(0)}\rvert}{\lvert\dot{I}_{b(1)}\rvert} + \frac{\lvert\dot{I}_{b(0)}\rvert}{\lvert\dot{I}_{b(2)}\rvert} + \frac{\lvert\dot{I}_{b(1)}\rvert}{\lvert\dot{I}_{b(2)}\rvert} < 3+\varepsilon$
A_3	$3-\varepsilon < \frac{\arg\dot{I}_{b(0)}}{\arg\dot{I}_{b(1)}} + \frac{\arg\dot{I}_{b(0)}}{\arg\dot{I}_{b(2)}} + \frac{\arg\dot{I}_{b(1)}}{\arg\dot{I}_{b(2)}} < 3+\varepsilon$
A_4	$3-\varepsilon < \frac{\lvert\dot{I}_{c(0)}\rvert}{\lvert\dot{I}_{c(1)}\rvert} + \frac{\lvert\dot{I}_{c(0)}\rvert}{\lvert\dot{I}_{c(2)}\rvert} + \frac{\lvert\dot{I}_{c(1)}\rvert}{\lvert\dot{I}_{c(2)}\rvert} < 3+\varepsilon$
A_5	$3-\varepsilon < \frac{\arg\dot{I}_{c(0)}}{\arg\dot{I}_{c(1)}} + \frac{\arg\dot{I}_{c(0)}}{\arg\dot{I}_{c(2)}} + \frac{\arg\dot{I}_{c(1)}}{\arg\dot{I}_{c(2)}} < 3+\varepsilon$

Collection B, C, D is shown in table 3, table 4 and table 5, respectively.

TABLE 3

CHARACTER COLLECTION B

B_0	$-\varepsilon < \dot{I}_{a(0)} + \dot{I}_{a(1)} + \dot{I}_{a(2)} < \varepsilon$
B_1	$-2-\varepsilon < \frac{\arg\dot{I}_{a(0)}}{\arg\dot{I}_{a(1)}} + \frac{\arg\dot{I}_{a(2)}}{\arg\dot{I}_{a(1)}} < -2+\varepsilon$
B_2	$-\varepsilon < \dot{I}_{b(0)} + \dot{I}_{b(1)} + \dot{I}_{b(2)} < \varepsilon$
B_3	$-2-\varepsilon < \frac{\arg\dot{I}_{b(0)}}{\arg\dot{I}_{b(1)}} + \frac{\arg\dot{I}_{b(2)}}{\arg\dot{I}_{b(1)}} < -2+\varepsilon$
B_4	$-\varepsilon < \dot{I}_{c(0)} + \dot{I}_{c(1)} + \dot{I}_{c(2)} < \varepsilon$
B_5	$-2-\varepsilon < \frac{\arg\dot{I}_{c(0)}}{\arg\dot{I}_{c(1)}} + \frac{\arg\dot{I}_{c(2)}}{\arg\dot{I}_{c(1)}} < -2+\varepsilon$

TABLE 4

CHARACTER COLLECTION C

C_0	$-\varepsilon < \lvert\dot{I}_{a(0)}\rvert < \varepsilon$
C_1	$1-\varepsilon < \frac{\lvert\dot{I}_{a(1)}\rvert}{\lvert\dot{I}_{a(2)}\rvert} < 1+\varepsilon$
C_2	$-1-\varepsilon < \frac{\arg\dot{I}_{a(1)}}{\arg\dot{I}_{a(2)}} < -1+\varepsilon$
C_3	$-\varepsilon < \lvert\dot{I}_{b(0)}\rvert < \varepsilon$
C_4	$1-\varepsilon < \frac{\lvert\dot{I}_{b(1)}\rvert}{\lvert\dot{I}_{b(2)}\rvert} < 1+\varepsilon$
C_5	$-1-\varepsilon < \frac{\arg\dot{I}_{b(1)}}{\arg\dot{I}_{b(2)}} < -1+\varepsilon$
C_6	$-\varepsilon < \lvert\dot{I}_{c(0)}\rvert < \varepsilon$

C_7	$1-\varepsilon < \frac{\lvert\dot{I}_{c(1)}\rvert}{\lvert\dot{I}_{c(2)}\rvert} < 1+\varepsilon$
C_8	$-1-\varepsilon < \frac{\arg\dot{I}_{c(1)}}{\arg\dot{I}_{c(2)}} < -1+\varepsilon$

TABLE 5

CHARACTER COLLECTION D

D_0	$3-\varepsilon < \frac{\lvert\dot{I}_{a(1)}\rvert}{\lvert\dot{I}_{b(1)}\rvert} + \frac{\lvert\dot{I}_{a(1)}\rvert}{\lvert\dot{I}_{c(1)}\rvert} + \frac{\lvert\dot{I}_{b(1)}\rvert}{\lvert\dot{I}_{c(1)}\rvert} < 3+\varepsilon$
D_1	$-\varepsilon < \dot{I}_{a(0)} + \dot{I}_{a(2)} + \dot{I}_{b(0)} + \dot{I}_{b(2)} + \dot{I}_{c(0)} + \dot{I}_{c(2)} < \varepsilon$

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VIII. BIOGRAPHIES

Ziguan Zhou was born in Liaoning Province of China on Jun 11, 1981. He received his bachelor's degree from Southeast University in 2003, and master's degree form Peking University in 2006. Now he is a Ph.D. candidate of China Electric Power Research Institute. His research interests are in system analysis and control, fault diagnosis and analysis in power system.

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