RCA METHOD FOR FAULT DIAGNOSIS IN DIGITAL SUBSTATIONS OF POWER SYSTEMS

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Keywords: Digital substation, Fault diagnosis, Root cause analysis, Dempster/shafer theory, Fishbone diagram.

Abstract: The authors present a Cause-Effect fault diagnosis model, which utilises the Root Cause Analysis approach and takes into account the technical features of a digital substation. The Dempster/Shafer evidence theory is used to integrate different types of fault information in the diagnosis model so as to implement a hierarchical, systematic and comprehensive diagnosis based on the logic relationship between the parent and child nodes such as transformer/circuit-breaker/transmission-line, and between the root and child causes. A real fault scenario is investigated in the case study to demonstrate the developed approach in diagnosing malfunction of protective relays and/or circuit breakers, miss or false alarms, and other commonly encountered faults at a modern digital substation.

1 INTRODUCTION

Fault diagnosis and accident treatment in substations have become a major challenge of reinforcing power systems' safety and reliability. Many integrated substation diagnosis models and methods have been proposed to address this challenge by using information obtained from protective relays and circuit breakers and employing technologies such as expert systems (Lee et al., 2000); (Jung et al., 2001); (Huang, 2002), artificial neural networks (Yang et al., 1994); (Cardoso et al., 2004), Petri networks (Huang and Mu, 2006); (Lo et al., 1997), agent technology (Dong and Xue, 2004), and rough sets (Hor and Crossley, 2007); (Dong et al., 2002). In addition, substation diagnosis models and methods may rely on a single transmission or transformation equipment as done by the transformer diagnosis model based on three chromatographic level correlation analysis (Michel and James, 2005), and the wavelet theory based transmission line fault diagnosis model using fault recorders (Silva et al., 2006). It is observed that the current substation fault diagnosis models only take into account information of protective relays and circuit breakers, or fault features of a single device. In other words, the existing models and methods, due to employing only local information, are difficult to diagnose certain complex faults with uncertainties, including multiple consecutive failures, malfunctions of protective relays and/or circuit breakers, missing or false alarms, and sensor errors, to name a few (Lee et al., 2000).

With advent of new technologies and tools such as intelligent primary/secondary equipment and IEC61850 communication standard, applications of digital technologies have become the trend in substation automation, calling for novel fault diagnosis methods and models with information sharing and interoperability of intelligent electrical devices in substations.

In the paper, the authors propose a Root Cause Analysis (RCA) based Cause-Effect (fishbone diagram) fault diagnosis model for digital

Peng P., Liao Z., Wen F. and Huang J..
RCA METHOD FOR FAULT DIAGNOSIS IN DIGITAL SUBSTATIONS OF POWER SYSTEMS.
DOI: 10.5220/0003627403700378
In *Proceedings of the International Conference on Evolutionary Computation Theory and Applications* (FCTA-2011), pages 370-378
ISBN: 978-989-8425-83-6

substations of power systems. The fusion rule of the well-developed Dempster/Shafer (D-S) evidence theory is used to integrate different types of fault information obtained through monitoring states of substations, protective relays and circuit breakers. Based on the logic relationship between the parent and the transformer/circuit breaker/transmission line child nodes, and between the root and the child causes, in the diagnosis model, an hierarchical, systematic, and comprehensive diagnosis can then be performed. A software package has been developed to implement the proposed fault diagnosis model and deployed in Xingguo Substation, the first digital substation in Jiangxi Province, China.

2 BASIC PRINCIPLES OF RCA

The RCA, originally applied in organization management (NELMS, 2007), is a hierarchical and systematic approach to identify and analyse the root cause, and then develop the countermeasures accordingly. A large substation comprises many components with interactions among them. Through analysing these interactions, a novel fault diagnosis model for substation transmission and transformation systems can be built up according to the structure and data/information flows of a digital substation. Based on the theory of RCA, the fault diagnosis model is formulated to explain the linkage chain of accident causes so that identify what really happened and the applicable countermeasures.

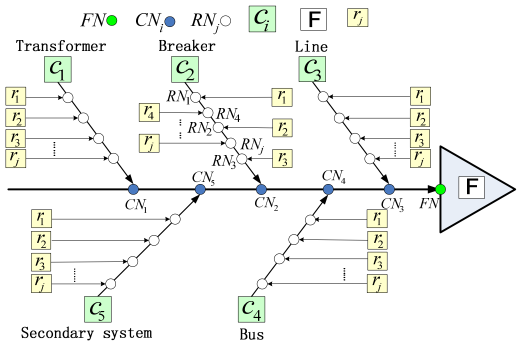

Figure 1: Framework of RCA-based fault diagnosis system for digital substations.

The research tools of RCA include Cause & Effect/Fishbone Diagram, Brain Storm and WHY-WHY Diagram. There are three types of Fishbone Diagrams: arrangement-based, cause-based and solution-based. As shown in Fig. 1, the cause-based fishbone diagram is adopted to explain the philosophy of applying the RCA in fault diagnosis of digital substations. The following is the explanation to each component of the diagram:

1) F : a problem node to be solved as a specified fault in a substation .

2) c_i : a child cause of F and a basic reason of a specified fault. $p(c_i)$ denotes the fault probability caused by c_i . $S(F) = \{c_1, c_2, \cdots, c_i\}$ is the set of child causes which could trig F .

3) r_j : a root cause of F and a fundamental reason of a specified fault in the power system. $p(r_j \mid c_i)$ denotes the conditional fault probability caused by r_j with given c_i and $G(c_i)=\{r_1,r_2,\ldots,r_j|c_i\}$ is the root cause set.

4) FN : the only parent node for the diagnosis system. $FN = (D, M, O)$, composed of three elements D , M and O , denotes the basic diagnosis functions. D represents the composition of the access modes to obtain the required information from the source $D \subseteq D_e = \{d_1, d_2, \cdots, d_n\}$, and D_e is the collection of all the n available modes. M= $\{met_1, met_2, \ldots, met_p\}$, denotes the p fault diagnosis methods applicable at the node. $O = \{[c_i, p(c_i)] \mid (i = 1, 2, \cdots, q)\}$ is the diagnosis output, where $c_i \in O$, q is the number of the reasons $\{ c_i \}$, and $p(c_i)$ denotes the fault probability caused by c_i .

5) CN_i and RN_j : the child nodes and the root nodes. Like FN , they are constituted by the three elements D , M , O . Furthermore, they can give a more detailed diagnosis based on that of FN . Thereinto, $S(CN)=\{CN_1, CN_2, \ldots, CN_i\} \subseteq FN$, with $S(CN)$ denoting the set of all the child nodes belonging to FN ; $S(RN|CN_k) =\{RN_1, RN_2, \ldots, RN_i\} \subseteq CN_k$ is the set of root node RN belonging to the child node CN_k .

6) From the node definition given in 4), it can be seen that all nodes, including FN , CN_i and RN_j , are independent in obtaining the information needed by the diagnosis, selecting the appropriate diagnosis methods, and analysing fault reasons of each node.

3 FAULT DIAGONOSIS OF DIGITAL SUBSTATION

A root cause analysis based fault diagnosis system for digital substations is shown in Fig. 1. $S(CN)=\{CN_1, CN_2, CN_3, CN_4, CN_5\}$ and $S(F)=\{c_1,c_2,c_3,c_4,c_5\}$ denote the child nodes and the child causes of transformers, circuit breakers, lines, bus and secondary system (DC power supply, network communications and security devices).

3.1 The Modes to Obtain Information

The Substation Configuration Description Language (SCL) is used to describe the IEC61850 standard based IED configuration and related parameters, communication system configuration, substation system structure, and the relationship among them for information exchanging. Logical node LN is the basic function unit of a digital substation to obtain the needed information. Part of the logic nodes required in the designed fault diagnosis is listed in Table 1:

Table 1: Main logic nodes in SCL.

Logical node		Explain
1.	Pxyz (Protective relay)	Protection operation
2.	XCBR (Circuit breaker)	Switch position
3.	RREC (Reclosing)	Reclosing operation
4.	XSWI (Knife switch)	Knife position
5.	SMIL (Online monitoring information of transformer oil chromatography)	Monitoring value
6.	SCBR (Online monitoring information of circuit breaker)	Monitoring value

For a comprehensive analysis and diagnosis of an accident, the required diagnosis information should also include various electrical and chemical test results of the equipment. The diagnosis information is divided into three types as following:

1) The location variant information, i.e., the remote information with time stamps.

2) The section information, including the information of remote communication and remote measurement at a certain time point.

3) The data files, including various electrical and chemical test results of equipment, chemical experiment results, overhaul history, waveform files of breaker and recorded faults via on-line monitoring.

3.2 The Parent and Child Nodes

The information access mode $D=\{d_1\}$ of a parent node $FN=(D,M,O)$ is a passive one in obtaining location variant information of Pxyz(Protective relay), XCBR(Circuit breaker), RREC(Reclosing) and secondary equipment. The diagnosis method $M = \{m_1\}$ based on the optimization algorithm developed in (Guo, Wen, Liao, Wei, and Xin, 2010), is to diagnose substation faults with information obtained from protective relays, circuit breakers and secondary equipment. The output of the diagnosis is

$$O=\{[c_1, p(c_1)], [c_2, p(c_2)], [c_3, p(c_3)], [c_4, p(c_4)], [c_5, p(c_5)]\}$$

where c_1, c_2, c_3, c_4, c_5 respectively denote transformer faults, malfunction of protective relays and/or circuit breakers, line faults, bus faults, and malfunctions of secondary equipment (Fig. 2).

The child nodes such as CN_1, CN_2 and CN_3 are defined below:

1) The child node of transformer CN_1

The information access mode $D_1=\{d_2\}$ of child node $CN_1=(D_1,M_1,O_1)$ is an active mode in obtaining online monitoring information of the transformer oil chromatography. $M = \{m_1\}$ is the method to analyse the gas in the oil so as to diagnose transformer faults using the improved three-ratio method. $O_1=\{[r_j, p(r_j \mid c_1)] \mid j=1,2,\cdots,9\}$ is the output of the diagnosis, where r_1 is partial discharge, r_2 is type-1 low-temperature overheating(below 150^{o}C), r_3 is type-2 low-temperature overheating (150^{o}C-300^{o}C), r_4 is medium-temperature overheating, r_5 is high-temperature overheating, r_6 is low-energy discharge, r_7 is low-energy discharge and overheating, r_8 is arc discharge, and r_9 is arc discharge and overheating. $p(r_j \mid c_1)$ is the fault probability caused by r_j with given c_1.

2) The child node of circuit breaker CN_2

$D_2=\{d_1,d_2,d_3\}$ is the information access mode of child node $CN_2=(D_2,M_2,O_2)$, and d_1 is a passive mode in obtaining location variant information of XCBR, d_2 is an active mode in obtaining online monitoring information of SCBR, d_3 is an active FTP mode in obtaining online monitoring waveform files of circuit breakers. Based on the Dempster's Fusion Rule and expert knowledge-base, $M=\{m_2\}$ is the method to establish the set of state sign with online monitoring information, including switching coil current, switch waveform file, storage time of energy-storage motor, and current curves. The method diagnoses the faults of circuit breakers according to the coil switching current RMS and the elapsed time, the energy-storage motor storage time, the total distance of a circuit breaker's operation, the instantaneous and the average switching speed of a circuit breaker.

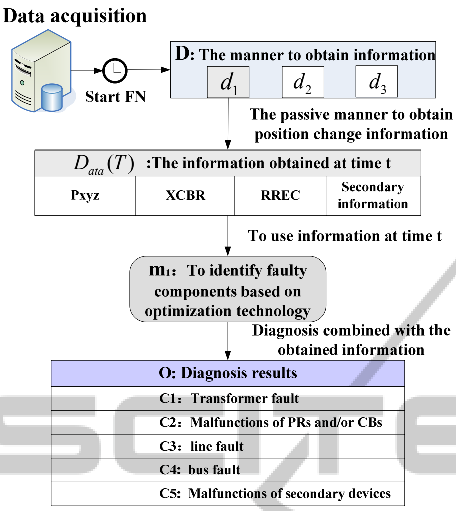

Figure 2: The functional diagram of FN.

$O_2 = \{[r_j, p(r_j \mid c_2)] \mid j = 1,2,\cdots,10\}$ is the output of the diagnosis, r_1: mismatch of the switching coil core and over resistance of switch operation, r_2: short circuit of the switching coil, r_3: burn or break of the switching coil, r_4: deformation or displacement of latch and valve connected to the core mandrel, r_5: poor contact and operation of auxiliary switch and closing contactor, r_6: fault of DC power or system auxiliary power, r_7: fault of operating mechanism, r_8: fault of energy-storage motor, r_9: mechanical failure, such as deformation and displacement of linkage unit, and latch failure, and r_{10}: short residual life. $p(r_j \mid c_2)$ denotes the fault probability caused by r_j with given c_2.

3) The child node of line CN_3

$D_3 = \{d_3\}$ is the information access mode of child node $CN_3 = (D_3, M_3, O_3)$, d_3 is the active FTP mode to obtain recorded line fault files (Contrade). $M = \{m_3\}$ is the method that utilizes the sudden-change of the phase current difference to select the phase and then locate the fault by estimating the distance with the sampled data from the recorded fault curve. $O_3 = \{[r_j, p(r_j \mid c_2)] \mid j = 1,2,3,4\}$ is the output of the diagnosis, with r_1 as single phase grounding fault, r_2 as double phase grounding fault, r_3 as inter-phase short circuit fault, r_4 as three phase short circuit fault. $p(r_j \mid c_3)$ denotes the fault probability caused by r_j with given c_3. In addition, the identified fault location is included in the diagnosis output (Fig. 3).

4 THE FAULT DIAGONOSIS FLOWCHART BASED ON RCA

As illustrated by the flowchart in Fig. 4, the RCA based fault diagnosis includes two cases.

4.1 Without Operation of Protective Relaying, Circuit Breaking and Reclosing

This case is mainly for monitoring and evaluating the status of transmission and transformation equipment. Each child node (D, M and O) is started periodically with a timer interval $t_{interval}$. According to the output of child nodes CN_1, CN_2 and CN_5, the state of transmission and transformation equipment of the substation is evaluated, with the evaluation results O_1, O_2, O_3, O_5 and R as given in Eqn. (1).

$$R = O_1 \cup O_2 \cup O_3 \cup O_5 = \begin{Bmatrix} [(r_j \mid c_1), p(r_j \mid c_1)] \\ [(r_j \mid c_2), p(r_j \mid c_2)] \\ [(r_j \mid c_3), p(r_j \mid c_3)] \\ [(r_j \mid c_5), p(r_j \mid c_5)] \end{Bmatrix} \quad (1)$$

4.2 With Operation of Protective Relaying, Circuit Breaking and Reclosing

The major analysis and diagnosis procedure of this case is as following:

1) Once the protective relays, circuit breakers and reclosers operate, the diagnosis M of FN is started, to obtain the location variant information of Pxyz, XCBR, RREC and secondary equipment by mode d_1. In the diagnosis, the optimization technology is employed to identify the faulty components and provide the child cause set of fault as shown in Eqn. (2).

$$S(F) = O = \{[c_1, p(c_1)], [c_2, p(c_2)], [c_3, p(c_3)], [c_4, p(c_4)], [c_5, p(c_5)]\} \quad (2)$$

2) Due to the lag in acquiring various waveform files compared with obtaining the location variant information, a delay of t_{delay} is introduced to start each child node.

3) To avoid conflicts between the parent node and child node due to potential errors existing in information source, the set of all possible faults is used as the basis of the diagnosis, and each symptom of faults is used as the evidence in conducting the comprehensive analyse to the output of FN, O, O_1, O_2, O_3 and O_5. The frame of discernment is the basic concept of D-S evidence theory. For a judgment problem, all possible results that can be recognized are expressed by Θ, a non-empty set known as the frame of discretion. The frame consists of a number of mutually exclusive and exhaustive elements. $\Theta = \{q_1, q_2, q_3, q_4, q_5\}$, where q_1 is a transformer fault, q_2 is malfunction of protective relays and/or circuit breakers, q_3 is a line fault, q_4 is a bus fault and q_5 is malfunction of secondary equipment.

If $m(q_i)$, the assigned value to function m by proposition q_i, meets the following conditions:

$$m(\Phi) = 0 \tag{3}$$

$$\forall q_i \in \Theta, \ m(q_i) \geq 0, 且 \sum_{q_i \in \Theta} m(q_i) = 1 \tag{4}$$

$m(q_i)$ is known as the basic probability assignment function (BPAF) of q_i, which reflects the belief to the accuracy of q_i, i.e., the direct support to q_i but no support to any subset of q_i. Furthermore, $m(q_i)$ is defined as the focus element of evidence if q_i is a subset of Θ and $m(q_i)$>0. Φ represents an empty set in Eqn. (3). Here the diagnosis result of FN is taken as Evidence-1 corresponding to the BPAF $m_1(q_k)$, and the diagnosis result of CN is taken as Evidence-2 corresponding to the BPAF $m_2(q_l)$. $m_1(q_k)$ and $m_2(q_l)$ are supposed to be the two BPAF of independent evidence in the same frame of discernment Θ. While m_1 is the BPAF of Evidence-1 with $m_1(q_k) = p(c_i)$, m_2 is the BPAF of Evidence-2 with $m_2(q_l) = p(r_j \mid c_i)$.

The D-S Fusion Rule is to reflect the joint effect of the evidences in the same frame of discernment through calculating a single BPAF with the BPAFs of different evidences. By applying the rule, the joint effect of Evidence-1 and Evidence-2 is evaluated in Eqn. (5).

$$m(q) = \frac{\sum_{q_k \cap q_l = q} m_1(q_k) m_2(q_l)}{\sum_{q_k \cap q_l \neq \Phi} m_1(q_k) m_2(q_l)} = m_1(q_k) \oplus m_2(q_l) \tag{5}$$

where $m(q)$ is the orthogonal sum of $m_1(q_k)$ and $m_2(q_l)$, denoted by $m = m_1 \oplus m_2$.

$$\sum_{q_k \cap ql \neq \Phi} m_1(q_k) m_2(q_l) = 1 - \sum_{q_k \cap q_l = \Phi} m_1(q_k) m_2(q_l) = 1 - k \tag{6}$$

where $k = \sum_{q_k \cap q_l = \Phi} m_1(q_k) m_2(q_l)$ expressing the conflict degree resulted in the fusion course of the evidences, and 0≤k≤1. In general, the larger the k, the more intense conflicts are among the evidences.

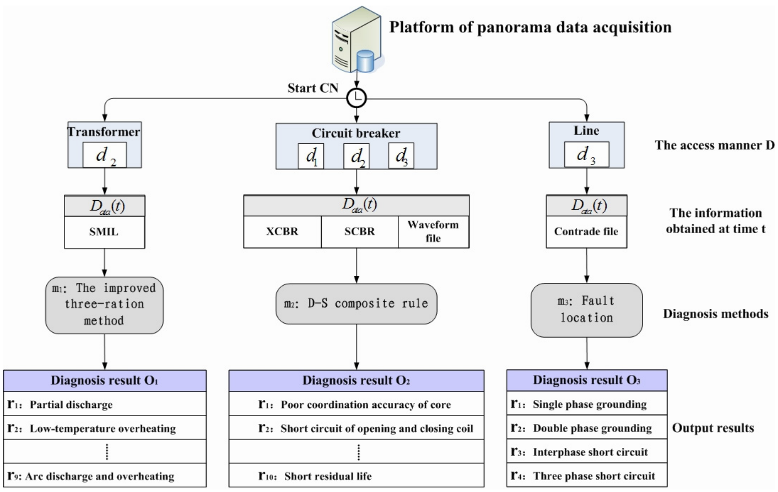

Figure 3: The functional diagram of CN.

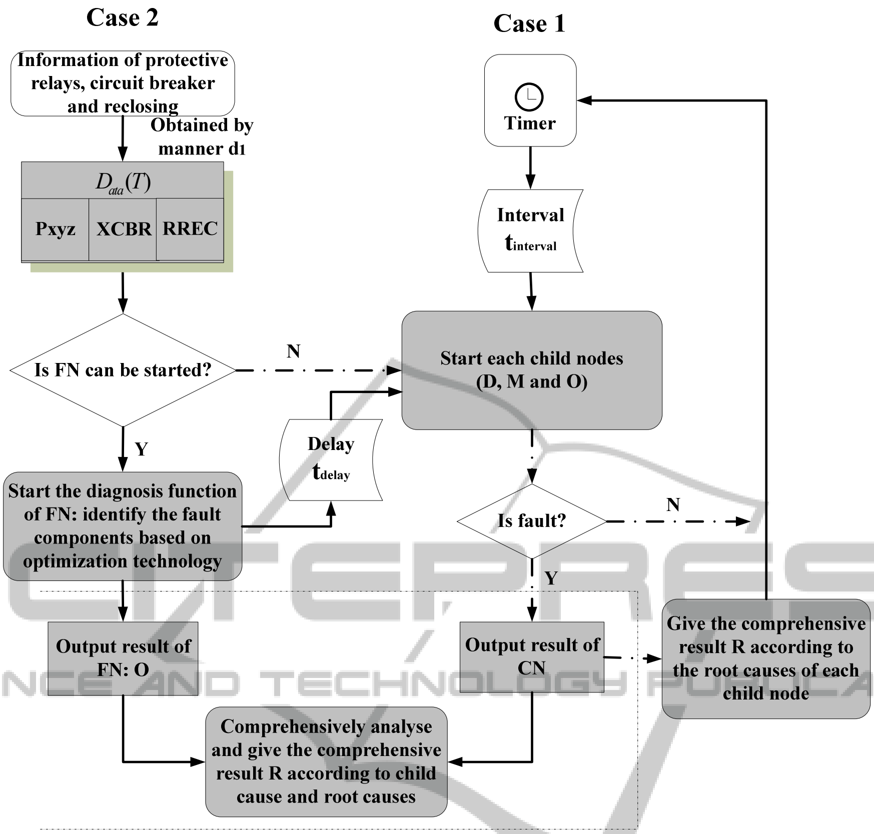

Figure 4: The RCA based fault diagnosis.

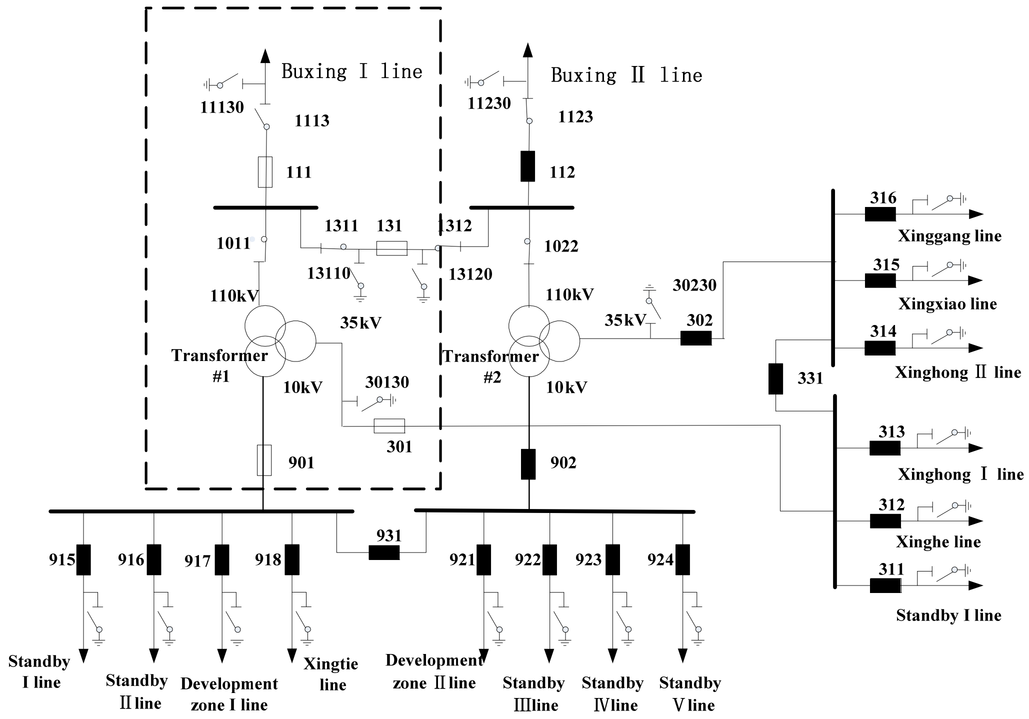

Figure 5: The main connection scheme of the 110 kV Xingguo digital substation.

Table 2: Location variant information obtained by mode d_1.

Time	Alarm ID	Alarm value	Alarm description
2009-12-20 15:20:12 50ms	PCOS_PZB1H/Q0PTOC3 STOp$general	1	Operation of overcurrent, segment-2, 1st time, limit of high reserve for transformer 1#
2009-12-20 15:20:13 150ms	PCOS_P110LINE1/Q0XC BR1STPos$stVal	1	Operation of circuit breaker numbered 111
2009-12-20 15:20:13 260ms	PCOS_PZB1L/Q0XCBR1 STPos$stVal	1	Operation of circuit breaker numbered 901
2009-12-20 15:20:13 327ms	PCOS_PZB1M/Q0XCBR 1STPos$stVal	1	Operation of circuit breaker numbered 301
2009-12-20 15:20:13 383ms	PCOS_ P110LINE3/Q0XCBR1$S T$Pos$stVal	1	Operation of circuit breaker numbered 131

Table 3: Online monitoring information of transformer oil chromatography obtained by mode d_2.

Time	Alarm ID	Alarm value	Alarm description
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXH2magf	35	Hydrogen measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXCH4magf	12	Methane measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H4magf	15	Ethylene measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H2magf	0	Acetylene measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H6magf	8	Ethane measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXCOmagf	406	Carbon monoxide measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXCO2magf	120	Carbon dioxide measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXTHCmagf	35	THC measurement of transformer 1#(uL/L)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXH2AbsRtemagf	1	Absolute gas production rate of hydrogen of transformer 1#(uL/d)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H2magf	0	Absolute gas production rate of methane of transformer 1#(uL/d)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H2magf	0.5	Absolute gas production rate of ethene of transformer 1#(uL/d)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H6magf	0	Absolute gas production rate of acetylene of transformer 1#
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H6magf	0	Absolute gas production rate of ethane of transformer 1#(uL/d)
2009-12-20 15:20:23	PCOS_YSP1/Q0SIML0MXC2H6magf	0.5	Absolute gas production rate of THC of transformer 1#(uL/d)

Table 4: The Composite results.

BPAF of nodes	q_1	q_2	q_3	q_4	q_5
m_1	0.4	0	0.6	0	0
m_2	0	0	1	0	0
$m = m_1 \oplus m_2$	0	0	1	0	0

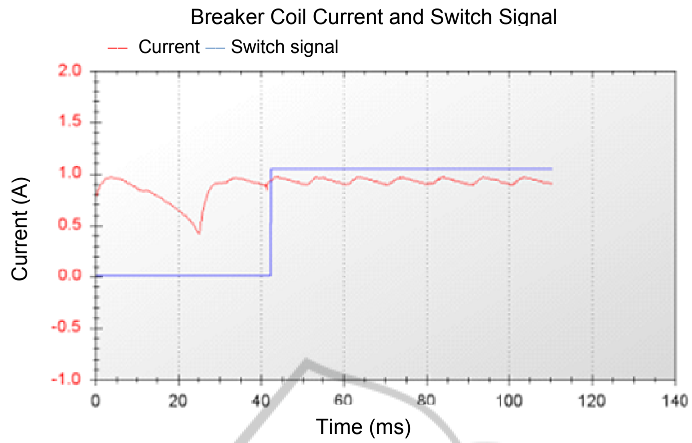

Figure 6: Coil current and switch signal waveform of circuit breaker numbered 111 obtained by mode d_3.

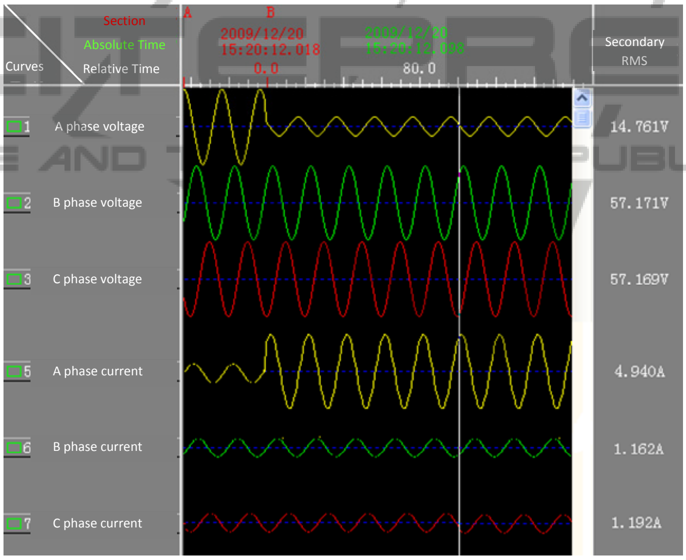

Figure 7: The fault recording curves of Buxing I line obtained by mode d_3.

5 CASE STUDY

The developed software package has been applied in the 110 kV Xingguo digital substation, the first digital substation in Jiangxi Province, China. The power outage region due to a fault is circled by the dotted lines as shown in Fig. 5.

1) The location variant information is obtained by mode d_1 (Table II). $D_{ata}(T)$ denotes the information obtained from 2009-12-20 15:20:12 50ms to 2009-12-20 15:20:13 383ms.

2) The diagnosis function M of FN is started to identify the faulty components and then provide the child cause set of the fault $S(F) = O = \{[c_1, 0.4], [c_2, 0], [c_3, 0.6], [c_4, 0], [c_5, 0]\}$ which reveals that the probability is 0.4 for a transformer fault, and is 0.6 for a line fault.

3) The online monitoring information of transformer oil chromatography is obtained by mode d_2 (Table III). The coil current and switch signal waveform of the circuit breaker numbered 111 is obtained by mode d_3 (Fig. 6). The recorded fault curves of Line Buxing I is obtained by mode d_3 (Fig. 7). A 10s delay t_{delay} is set to start the child nodes CN_1, CN_2, CN_3 and CN_5. Finally the root cause has been identified as a single phase grounding fault in Line Buxing I $O_3 = \{[r_1, 1]\}$.

4) According to the D-S Fusion Rule, the diagnosis result is obtained as given in Table IV:

$$k = \sum_{q_k \cap q_l = \Phi} m_1(q_k) m_2(q_l) = 0.4 \times 1 = 0.4$$

$$m(q_3) = \frac{\sum_{q_k \cap q_l = q_3} m_1(q_k) m_2(q_l)}{\sum_{q_k \cap q_l \neq \Phi} m_1(q_k) m_2(q_l)} = \frac{0.6}{1 - 0.4} = 1$$

Before the fusion, it can be seen that, the parent node's supporting is 0.4 to q_1 and is 0.6 to q_3. The parent node does not support q_2, q_4, and q_5. The child nodes support only q_3. Once combined, both of the parent node and the child nodes support only q_3. The fusion result supports the common part of the diagnosis results, and discards the conflicting ones. The fusion result, i.e., the single phase grounding fault of Line Buxing I, agrees with the actual fault of the substation.

6 CONCLUSIONS

By taking into account the structure and technical features of digital substations, the authors develop a Root Cause Analysis based approach to diagnose faults of transmission and transformation equipment of large substations. The D-S evidence theory is applied to analyse thoroughly the comprehensive fault information of transmission and transformation equipment to find the root cause. The developed fault diagnosis system can be used to diagnose various faults commonly encountered in substations, including malfunctions of protective relays and/or circuit breakers, and miss or false alarms. The diagnosis system can be implemented in a hierarchical structure for multi-level information integration. A real fault scenario was used in the case study to demonstrate the effectiveness of the proposed fault diagnosis system. The performance of the developed software package has been verified by the case study.

REFERENCES

Lee, H. J. B., Ahn, S., Park, Y. M., (2000). A fault diagnosis expert system for distribution substations. *IEEE Transactions on Power Delivery*, vol. 15, no. 1, January 2000, 92-97.

Jung, J. W., Liu, C. C., Hong, M. G., Gallanti, M., Tornielli, G., (2001). Multiple hypotheses and their credibility in on-line fault diagnosis. *IEEE Transactions on Power Delivery*, vol. 16, no. 2, April 2001, 225 - 230.

Huang, Y. C., (2002). Fault section estimation in power systems using a novel decision support system. *IEEE Transactions on Power Systems*, vol. 17, no. 2, May 2002, 438 – 444.

Yang, H. T., Chang, W. Y., Huang, C. L., (1994). A new neural network approach to on-line fault section estimation using information of protective relays and circuit breakers, *IEEE Trans on Power Delivery*, vol. 9, no. 1, 1994, 220 - 230.

Cardoso, G. J., Rolim, J. G., Zurn, H. H., (2004). Application of neural-network modules to electric power system fault section estimation. *IEEE Transactions on Power Delivery*, vol. 19, no. 3, July 2004, 1024 - 1041.

Huang, J. B., Mu, L. H., (2006). Fault diagnosis of substation based on Petri Nets technology. *Proceedings of 2006 International Conference on Power System Technology*, Oct. 2006, 1 - 5.

Lo, K. L., Ng, H. S., Trecat, J., (1997). Power systems fault diagnosis using Petri nets. *IEE Proceedings: Generation, Transmission and Distribution*, vol. 144, no. 3, May. 1997, 231 - 236.

Dong, H. Y., Xue, J. Y., (2004). An approach of substation remote cooperation fault diagnosis based on multi-agents. *Proceedings of the Fifth World Congress on Intelligent Control and Automation*, June 2004, 5170 - 5174.

Hor, C. L., Crossley, P. A., (2007). Building knowledge for substation-based decision support using rough sets. *IEEE Transactions on Power Delivery*, vol. 22, no. 3, July 2007, 1372 - 1379.

Dong, H. Y., Zhang, Y. B., Xue, J. Y., (2002). Hierarchical fault diagnosis for substation based on rough set. *Proceedings of 2002 International Conference on Power System Technology*, October 2002, 2318 - 2321.

Michel, D., James, D. J., (2005). Improving the reliability of transformer gas-in-oil diagnosis. *IEEE Electrical Insulation Magazine*, vol. 21, no.4, p 21-27.

Silva, K. M., Souza, B. A., Brito, N. S. D., (2006). Fault detection and classification in transmission lines based on wavelet transform and ANN. *IEEE Trans. Power Delivery*, 2006, vol 21, No. 4, 2058 – 2063.

NELMS, C. R., (2007). The problem with root cause analysis. *Proceedings of 2007 IEEE 8th Human Factors and Power Plants and HPRCT 13th Annual Meeting*, Aug. 2007, 253 - 258.

Guo, W. X., Wen, F. S., Liao, Z. W., Wei, L. H., Xin, J. B., (2010). An Analytic Model-Based Approach for Power System Alarm Processing Employing Temporal Constraint Network. *IEEE Transactions on Power Delivery*. Vol 25, No. 4, October 2010, 2435 – 2447.