Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Power Transformer Fault Diagnosis Based on Data Fusion

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Abstract: As the fault information of power transformers has characteristics such as complementarities, redundancy and uncertainty, the diagnosis task can't be finished by the simple fault characteristic vector and the diagnosis method. The basic ideas of information fusion are introduced, and DGA (the Dissolved Gas Analysis) is combined tightly with other information such as the results of conventional electrical test of power transformer. The power transformer fault diagnosis model based on information fusion is built. The models can diagnose both fault property and fault spot, which can improve reliability and lower uncertainty in fault diagnosis.

1. INTRODUCTION

As important equipment in power system, the power transformer's fault diagnosis technology is a research hotspot all the time. Its safe running state is related the security and economics of the whole power system, once the fault happened, one light point is that the production would be effected and the electric energy production is reduced; a catastrophic fluctuation is the life and wealth, and which would effect the whole national economic development. Tsinghua University discussed the sampling current sensor deeply in the monitoring of large-scale transformer and motor's local electric discharge (LIN Du, *et al*.,2005), and introduced new method of fault characteristic identification(WANG Hang and TAN Kexiong,1998), and the digital morphology was used to extract the monitor information's wave character (LI Jian *et al*.,2001). The other side, XiAn Traffic University combined the gas analysis in the oil and the electric experiment result in the transformer's monitoring (QIAN Zheng, *et al*.,2002). All the work promoted the development of the online monitor and the fault diagnosis technology in a great degree. The basic thought of information fusion is introduced into the transformer's fault diagnosis in this paper, which can improve the diagnosis dependability and reduce the uncertainty maximum, and has important theory and practicality merit.

2. TRANSFORMER FAULTS

As important equipment in power system, the Power transformer's capacity is big and its failure rate is higher. According to the related materials, the effective monitoring and diagnosis to the equipment can reduce 25%-50% maintenance expense of equipment, and the possibility of trouble can reduce 75%, and the economic benefit is very obvious (HUANF Yaluo, *et al*., 2000). So one important method to guarantee the supply reliability is that the transformer state must be checked at any time and the potential fault must be founded and discharged.

Based on the accident and fault class's statistical information of 328 power transformers during 1990-1911 in power system, whose voltage class is 110KV or upward, the fault location include: winding、iron core、tap switch、lead wire、bushing、insulation、cooling system、air tightness、radiator and the other fault locations, the occurrence number of every kind of fault is in the following table (JIANG Weining, 2004).

Table 1 The occurrence number of every kind of fault

The kinds of faults	times
Fault of winding	112
Fault of iron core	65
Fault of tap switch	37
Fault of leading wire	25
Fault of bushing	29
Fault of insulation	15
Fault of cooling system	7
Fault of transformer	4
Fault of accessory	9
Air tightness	12
The other faults	13
total	328

3. MULTI-SENSOR INFORMATION FUSION TECHNOLOGY

Multi-sensor information fusion technology dealt with the information came from different sources, and the aim is to get the optimal estimation result for the measured object or the process through using and cooperating with the multi-sensor information (HUWenping, *et al*.,2002). At present, this technology is used in intelligent manufacture, process monitor, robot, navigation, target identification, medical diagnosis and so on, but the using in power system is at the primary stage and the deep research and discussion are need to do in network running and controlling, power equipment state monitoring, fault diagnosis technology and power dispatching and so on; If the fault is diagnosed by the data integration and information fusion technology that the reliability of fault diagnosis is improved(Wang Wenzhi and Yu Fang, 2003) .

Information fusion include data layer, character layer, decision layer, who can synthesize the data or information came from multi-sensor or multi-source to get more accurate and reliable conclusion, and corresponding fusion levels and algorithms can be chosen according to different application background. The transformer fault diagnosis model is established based on information fusion technology after the DGA combined the electrical test and the other information. The layering decision to the transformer fault can judge not only the fault property, but also the fault location preliminary.

Shafer said: "The effect to some proposition A by the evidence includes two pieces of information at least, the belief degree of A and the belief degree of its negate proposition $\overline{A}$". The two pieces of information are denoted by the proposition's belief degree and plausibility degree. For all the $A \subseteq \Omega$, there are the following definitions:

$$Bel(A) = \sum_{B \subseteq A} m(B) \qquad (1)$$

$$Pl(A) = 1 - Bel(\overline{A}) = \sum_{B \cap A \neq \Phi} m(B) \qquad (2)$$

$Bel(A)$、 $Pl(A)$ and $Bel(\overline{A})$ are belief function、plausibility function and negative function of proposition A .

Definition: Let m_1 and m_2 is the basic probability assignment on 2^{Ω} which is mutually independent, the focal element is $A_1, \cdots, A_k$ and $B_1, \cdots, B_r$, and $K_1 = \sum_{\substack{i,j \\ A_i \cap B_j = \phi}} m_1(A_i) m_2(B_j) < 1$,then

$$m(C) = \begin{cases} \dfrac{\sum_{\substack{i,j \\ A_i \cap B_j = A}} m_1(A_i) m_2(B_j)}{1 - K_1} & \forall C \subset \Omega and C \neq \phi \\ 0 & C = \phi \end{cases} \qquad (3)$$

In the equation, if $K_1 \neq 1$, m determine a basic probability assignment; if $K_1 = 1$, m_1 and m_2 is contradictory, the basic probability assignment can't be combined; when $K_1 \to 1$, the regularization process for the high-conflict evidence will lead to the result which is paradoxical to the intuition, (Yong D. and Wen-kang S.,2003):

Theorem: Supposing $e_1, e_2, \cdots e_m$ is m evidences, for $e_j (j \leq m)$, if $m(\bullet / e_j)$ is the mass function on the identification frame Θ and if $P(e_j)$ is the probability of e_j, then $m(A) = \sum_{j=1}^{m} m(A / e_j) \cdot P(e_j)$, $(A \subset \Theta)$.

4. TRANSFORMER FAULT DIAGNOSIS MODEL BASED ON HIERARCHICALCLASSIFICATION

The accurate fault diagnosis demands many supports of multi-source information, namely the higher diagnosis request, the more information of every respect. In order to adapt the characteristics "multi-layer" of the transformer fault diagnostic information, the hierarchical decision model is put forward to look for the support information gradually, which make go deep into the transformer fault diagnosis continuously, near to the fault's true conditions gradually; On the other hand, the adoption hierarchical decision also lowers complexity of identifying frame, and reduces the calculation quantity of evidence combination, so as to raise the efficiency of evidence inference, Fig.1 is the transformer fault diagnosis hierarchical decision model based on evidence theory.

4.1. First-level decision fusion

The target of first-level diagnosis is to determine whether the fault happened or not.

The diagnosis analysis of this layer is based on the on-line monitoring of the transformer's running state directly. The DGA technique is one of the most convenient and the most valid means to diagnose for the oil transformer, and this level fusion fault diagnosis is established on the base of DGA.

In Fig.1 The abnormal phenomenon, the gas remark value, aerogenesis speed, the gas content measurement result after load down all hemi-emphasized on the monitoring of transformer's state, and whether the fault happened was judged; the fault was judged with the key gas method and the new guide rule of IEC-60599 when the evidence was existed; the first-level fused the judging result to determine the fault style.

Evidence dimension of First-level fusion is $E = \{e_i\}, i = 0,1,\cdots,n$, e_i denotes: "the gas content measurement result after load down", "key gas method", "new guide rule of IEC-60599"and so on, the adequate evidence is chosen to make up the evidence space according to the actual evidence; the first-level fusion identification frame is $\Theta_0 = \{F_0, F_1, F_2\}$, in the equation, F_0 is "no fault", F_1 is "fault of discharge", and F_2 is "fault of overheat" .

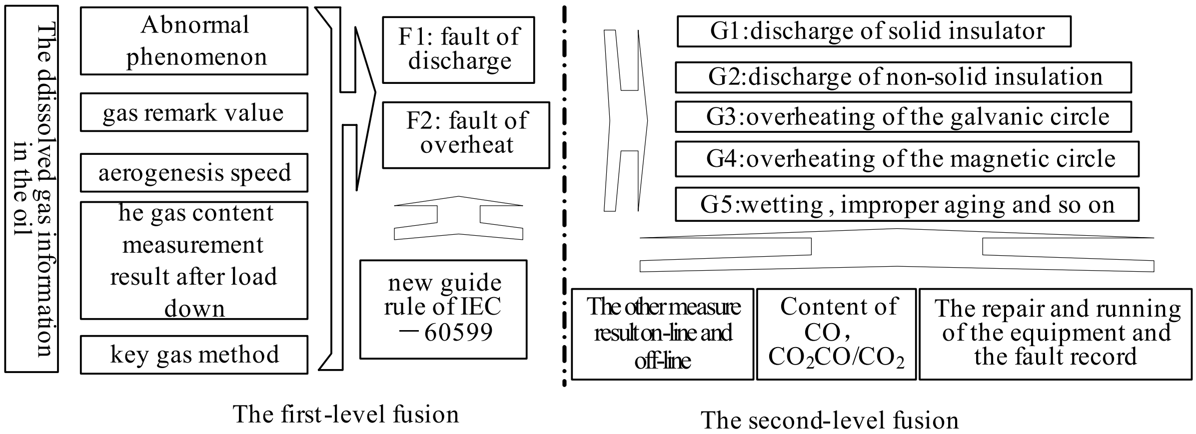

Fig. 1 the transformer fault diagnosis hierarchical decision model based on evidence theory

4.2 Second-level fault diagnosis decision fusion

The second-level diagnosis decision continue to seek the correspond evidence and judge the fault location farther, which make the conclusion of fault diagnosis accurate and fine gradually on the base of the first-level decision. Corresponding to the refinement of the identification frame, this kind of fault judging hierarchy is clearer, so the detailed information of the fault spot is got. Laying identification frame of the fault location is determined on the base of thorough research to the transformer's fault location. The first layer identification frame is $\Theta_1 = \{G_1, G_2, G_3, G_4, G_5\}$, in the equation, G_1 is related to "discharge of solid insulator", G_2 is related to "discharge of non-solid insulation", G_3 is related to "overheating of the galvanic circle", G_4 is related to "overheating of the magnetic circle", G_5 is related to "wetting , improper aging and so on". The judging of this layer is established on the base of the first-level decision fusion, the fault location is classified roughly, and the approximate range of fault location is determined.

The rough classified fault G_1, G_2, G_3, G_4, G_5 is refined further based on the fault's location and reason. On the identification ground of Θ_1, it is reasonable to refine the frame further according to the strong independence between each fault supporting evidence; Under the support of enough evidences, the result of judging will be more accurate, which is instructive for fault elimination and transformer maintenance. The layer allocation model of the transformer's fault is Fig.2

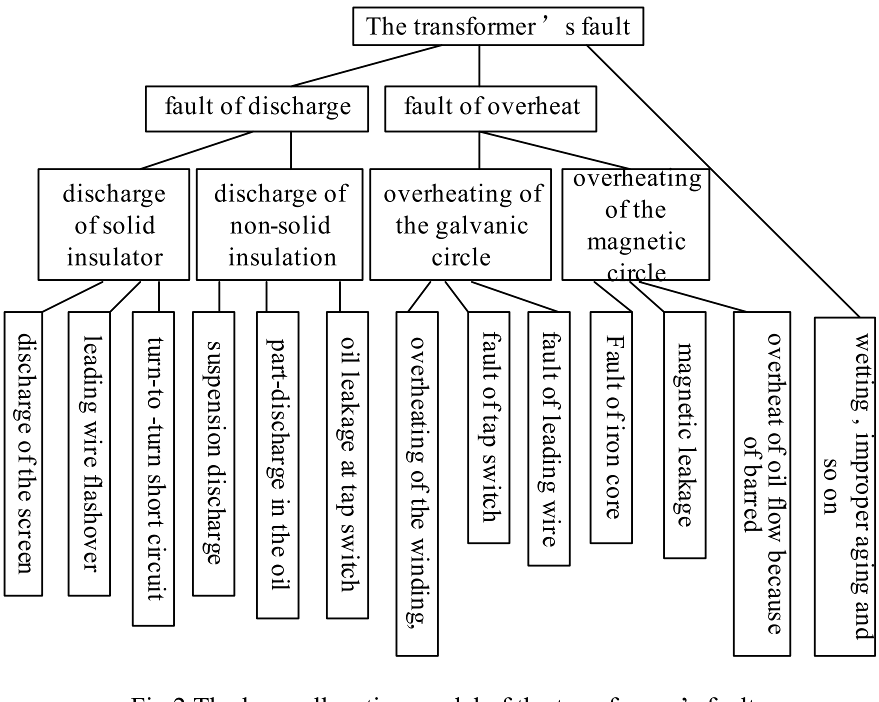

Fig.2 The layer allocation model of the transformer's fault

$G_1 = \{h_1, h_2, h_3\}$, in the equation, h_1, h_2, h_3 represents discharge of the screen, leading wire flashover and turn-to-turn short circuit individually;

$G_2 = \{h_4, h_5, h_6\}$, in the equation, h_4, h_5, h_6 represents suspension discharge, part-discharge in the oil and oil leakage at tap switch individually;

$G_3 = \{h_7, h_8, h_9\}$, in the equation, h_7, h_8, h_9 represents overheating of the winding, fault of tap switch and fault of leading wire individually;

$G_4 = \{h_{10}, h_{11}, h_{12}\}$, in the equation, h_{10}, h_{11}, h_{12} represents multiple earthing of the iron core, magnetic leakage and local pyrexia, overheat of oil flow because of barred individually;

G_5 represents wetting, improper aging and the others.

The corresponding data of off-line experiment is demanded on this layer in the judging, and these evidences are fused by use of the D-S evidence rule to infer the fault location.

5. EXAMPLE SIMULATION ANALYSIS

Some main transformer model : SFZ_9-31500/110, Weight of oil: 11.2t , which was put into production in April of 1997 .The oil temperature up to 66^0C is in disagreement with the circumstance temperature of 18^oC and burden of 20000kVA at that time in March 25, 2000. It was inferred that the main transformer occurred the fault of overheat. The analysis of the dissolved gas in the transformer's oil is present by the table 2 (Ming Dong, *et al.*,2005) .

Table 2. The analysis of dissolved gas in the transformer's oil($\times 10^{-6}$)

Time	composition							
	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	Total hydrocarbon	CO	CO_2
Put into production	0.1	0.2	0.0	0.1	0.0	0.3	100	305
Discover abnormality	10.0	15.0	5.0	19.5	0.0	39.5	700	2500
Sampling	11.0	18.0	6.1	24.5	0.0	48.6	720	2565
Run under a third of the burden	13.0	20.4	7.0	31.0	0.0	58.4	730	2600

The diagnosis step is as follows:

1) The identifying frame of first-level decision is $\Theta_0 = \{F_0, F_1, F_2\}$, evidence dimension is $E = \{e_1, e_2, e_3\}$, e_1,e_2,e_3,separately represent the measurement of gas content after load down(Assign to m_1), Key gas(Assign to m_2), new guide rule IEC-60599 diagnosis(Assign to m_3) is as follows:

e_1: The gas content is still increasing after a third of the burden, So Fault occurred;

e_2: It revealed that oil paper is superheated by key gas method;

e_3: New guide rule IEC-60599 diagnosed: high temperature overheated fault while $T \geq 700^0$C.

2) The mass function of first-level decision fusion is gotten on the ground of through evaluating and analyzing the evidence, the mass function is in table 3.

Table 3 first-level decision mass function

fault	evidence					
	e_1	$\bar{e}_1$	e_2	$\bar{e}_2$	e_3	$\bar{e}_3$
$\{F_1\}$	0	0.600	0.150	0.150	0	0.808
$\{F_2\}$	0.900	0.300	0.850.	0.850	0.850	0
$\{\Theta_0\}$	0.100	0.100	0	0	0.150	0.192
$P(e_i)$	0.85	0.15	1	0	1	0

The fusion result is as following, which combined prior probability according to the theorem. The belief degree of F_1(the fault of discharge)is 0, namely it is impossible to happen, but the belief degree of F_2(the fault of overheat) is 0.96, namely very strong supporting belief degree, and it is clear that the stronger supporting evidence is got through evidence fusion, so the fault style is judged as the fault of overheat, and it is overheating of the galvanic circle or overheating of the magnetic circle possibly, and first-level fusion result is in the table 4.

Table 4 First-level fusion result

evidence	fault			
	$\{F_0\}$	$\{F_1\}$	$\{F_2\}$	$\{\Theta_0\}$
Evidence1	0	0	0.765	0.235
Evidence2	0	0.15	0.85	0
Evidence3	0	0	0.85	0.15
result	0	0	0.96	0.04

3) The corresponding evidence was looked for in the second-level decision continuously, the iron core insulate resistance to the ground was near to 0 abnormally in the cut-off power measurement. The iron core insulate resistance to the ground was taken as the evidence e_4, the evidence had a stronger supporting belief degree to the overheating of the magnetic circle; $CO/CO_2$was taken as evidence e_5 , from table 2, CO/CO_2=0.218， it is between 0.09 and 0.33, the evidence had a weaker supporting belief degree to the overheating of the magnetic circle. Because the stronger belief degree of evidence, the fault was determined as the overheating of the magnetic circle primary, $G4=\{h_{10},h_{11},h_{12}\}$， in the equation, h_{10},$h_{11}$and h_{12} represented multiple earthing of the iron core, magnetic leakage and local pyrexia, overheat of oil flow because of barred individually. Because the supporting

evidence was short for $h_{11}$and h_{12}, the second-level decision function is gotten on the base of statistical analysis of the fault, such as table 5.

Table 5 second-level decision mass function

fault	evidence		fault	evidence	
	e_4	$\bar{e}_4$		e_5	$\bar{e}_5$
$\{h_{10}\}$	0.9	0.8	$\{h_{10},h_{11}\}$	0.2	0.1
$\{h_{11},h_{12}\}$	0.1	0.2	$\{h_{12}\}$	0.8	0.9
$P(e_i)$	0.8	0.2	$P(e_i)$	0.8	0.2

The second-level fusion result is in the table 6, which combined prior probability according to the theorem, the fault with the highest belief degree is h_{10}, namely the fault of multiple earthing of the iron core, because it's probability is the biggest, it is the main fault. At the same time the uncertainty of the fault judging was seen from the belief degree interval of the evidence, it is agree with the practical condition. In the practical hang-cage checking, the fault of overheat was found because of multiple earthing of the iron core, and the judging met the practice.

Table 6 second-level fusion result

evidence	fault					
	$\{h_{10}\}$	$\{h_{11}\}$	$\{h_{12}\}$	$\{h_{10},h_{11}\}$	$\{h_{11},h_{12}\}$	$\{\Theta\}$
Evidence 1	0.72	0	0	0.08	0	0.20
Evidence 2	0	0	0.02	0.18	0	0.80
result	0.60	0	0	0.02	0.06	0.32

6. CONCLUSION

D-S theory is the extension of the probability theory; It has weaker axiom schema and more strict inference process than probability theory, so it can reflect the uncertainty of the event. It is applied to the artificial intelligence field as a decision method with the help of fusion and inference. This paper established transformer fault diagnosis model with the application of D-S theory. It can increase the credibility of fault diagnosis effectively by the aid of multi-diagnosis information infusion. It proved the validity by the emulation test. So the information infusion diagnosis method based on D-S evidence theory has widespread availability.

ACKNOWLEDGEMENTS

This paper is sponsored by the National Science Foundation of China, the nature science foundation for Hebei Province, HeBei Province education department and the Research Fund of Hebei Normal University.

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