An Approach of Converter Transformer Condition Evaluation Based on The Belief Rule Base Inference Methodology and Evidence Reasoning

Qi Long[1,a], Yi Li[2,b], Yong Sun[3,c], Shaojun Yang[1,d], Qing Li[3,e], Youping Fan[2,f]

[1]CSG EHV Power Transmission Company, Guangzhou 510620, China

[2]School of Electrical Engineering, Wuhan University, Wuhan 430072, China

[3]Maintenance& Test Center, CSG EHV Power Transmission Company, Guangzhou 510663, China

[a]longqi@ehv.csg.cn, [b]dqliyi@whu.edu.cn, [c]sunyong@ehv.csg.cn, [d]yangshaojun@ehv.csg.cn, [e]liqing@ehv.csg.cn, [f]ypfan@whu.edu.cn

Keywords: converter transformer; condition evaluation; belief rule base; evidential reasoning; RIMER

Abstract. Various types of low-level indexes and uncertainty of evaluation information due to quantitative index and qualitative index exist in converter transformer condition evaluation. To solve this problem, a novel converter transformer condition evaluation approach based on the belief rule base inference methodology and evidence reasoning (RIMER) is proposed. It firstly builds rule base with belief structure and transforms input information to a pre-defined form, then calculates the activation weight of input, after that using evidence reasoning for index aggregation to get the final evaluation distribution. At last, a converter transformer condition evaluation in the 500kv converter station is investigated to illustrate the usage of the methodology and its advantages.

Introduction

Converter transformer is the very important equipment in the DC transmission system. Besides, it is the core equipment connecting both the converter and inverter station in HVDC system. Evaluating the converter transformer running state accurately and timely can reduce the maintenance cost, shorten the outage time, improve equipment utilization and the reliability level of the transmission system, which is the key to realize successfully converter transformer condition based maintenance. It has the important theory significance and practical value.

In view of various types of low-level indexes and uncertainty of evaluation information in the converter transformer condition evaluation, a novel converter transformer condition evaluation methodology based on the belief rule base and evidence reasoning (RIMER) is proposed in this article. It firstly builds rule base with belief structure and transforms input information to a pre-defined form, then calculates the activation weight of input, after that using evidence reasoning for index aggregation to get the final evaluation distribution. At last, a converter transformer condition evaluation in the 500kv converter station is investigated to illustrate the usage of the methodology and its advantages.

Theory of RIMER

RIMER has been put forward by professor Yang in 2006 as a kind of belief rule base and reasoning method based on evidential reasoning algorithm, with the modeling ability of uncertainty and fuzzy uncertainty and a probability of nonlinear characteristics of data . RIMER mainly includes two aspects: one is the expression of knowledge, the other is the knowledge reasoning. Knowledge expression is achieved through BRB(belief rule base) system while knowledge reasoning is through ER(evidential reasoning) algorithm.

Belief rule base. Belief rule base is a rule base which is composed of IF-THEN rules and each rule is belief structure. Rules in the rule base rules represented by Eq.1.

$$R_k : \text{If } x_1 = A_1^k \wedge x_2 = A_2^k \wedge \mathbf{L} \wedge x_{T_k} = A_{T_k}^k \text{ Then}\{(r_1, b_{1,k}), \mathbf{L}, (r_L, b_{L,k})\} \quad (1)$$

x is input vector, A_i^k is the reference value of the premise condition i in rule k. b_{ik} is the degree of

confidence of conclusion r_i in rule k while premise condition was established. By the way, $\sum_{l=1}^{L} b_{l,k} \le 1$. The relative weight of rule k is q_k ,while relative weights between the premise conditions in this rule is d_{k1}、d_{k2}、…、d_{kT_k}.

Evidence reasoning. When the input information x arrives, using the ER algorithm to combine the belief rules in BRB to get the final output of BRB system, this is the basic idea of RIMER. RIMER mainly through the following three steps to implement the BRB system of reasoning.

The activation weight of input information x to rule k is calculated through the formulas below

$$w_k = \frac{q_k \prod_{i=1}^{M} (a_i^k)^{\bar{d}_i}}{\sum_{l=1}^{L} q_l \prod_{i=1}^{M} (a_i^l)^{\bar{d}_i}} \tag{2}$$

$w_k \in [0,1]$,k=1,2,…,L; a_i^k (i=1,2,…M) is the degree of confidence of input x_i to the reference value A_i^k in rule k, $a_i^k \in \{a_{i,1}, a_{i,2}, \mathbf{L}, a_{i,J_i}\}$ The specific generated method of $a_{i,j}$ see Eq.16.Calculating correction factor shown as Eq.3~ Eq.4

$$m_k = \frac{\sum_{t=1}^{T_k} \left(f(t,k) \sum_{j=1}^{|A_t|} a_{t,j} \right)}{\sum_{t=1}^{T_k} f(t,k)}, f(t,k) = \begin{cases} 1, c_t \in R_k \\ 0, c_t \notin R_k \end{cases} \tag{3}$$

$$\bar{b}_{l,k} = b_{l,k} m_k \tag{4}$$

m_k donates for correction factor, the correction of the results. If the input information is complete, namely $\forall t$ and $\sum_{j=1}^{|A_t|} a_{t,j} = 1$,there is $\bar{b}_{l,k} = b_{l,k}$. T_k donates for the evaluation index number in rule k.

Using the ER algorithm. After the rule k is activated ,there is $w_k \ne 0$. The combination of BRB rules using the ER algorithm is mainly composed of the following two steps. Firstly, transfer the degree of confidence $\bar{b}_{l,k}$ of output part into basic probability form, as shown in Eq.5~Eq.8

$$m_{l,k} = w_k \bar{b}_{l,k} \tag{5}$$

$$m_{R,k} = 1 - w_k \sum_{l=1}^{L} \bar{b}_{l,k} \tag{6}$$

$$\bar{m}_{R,k} = 1 - w_k \tag{7}$$

$$\tilde{m}_{R,k} = w_k (1 - \sum_{l=1}^{L} \bar{b}_{l,k}) \tag{8}$$

$m_{l,k}$ the basic probability form assigned to conclusion l in rule k . $m_{R,k}$ is the basic probability form of that rule k is assigned to no conclusion, apparently $m_{R,k} = \bar{m}_{R,k} + \tilde{m}_{R,k}$ .Then fuse the multiple rules activated ($w_k > 0$) by the input. Might as well set the first S rules are activated ,the calculation process is as Eq.9~ Eq.14

$$m_{l,E(k+1)} = K_{E(k+1)} (m_{l,E(k)} m_{l,k+1} + m_{l,E(k)} m_{R,k+1} + m_{R,E(k)} m_{l,k+1}) \tag{9}$$

$$\bar{m}_{R,E(k+1)} = K_{E(k+1)} (\bar{m}_{R,E(k)} \bar{m}_{R,k+1}) \tag{10}$$

$$\tilde{m}_{R,E(k+1)} = K_{E(k+1)} (\tilde{m}_{R,E(k)} \bar{m}_{R,k+1} + \tilde{m}_{R,E(k)} \bar{m}_{R,k+1} + \bar{m}_{R,E(k)} \tilde{m}_{R,k+1}) \tag{11}$$

$$K_{E(k+1)} = \left(1 - \sum_{l=1}^{L} \sum_{t=1, t \ne l}^{L} m_{l,E(k)} m_{t,k+1} \right)^{-1} \tag{12}$$

$$b_l = \frac{m_{l,E(S)}}{1 - \bar{m}_{R,E(k+1)}} \tag{13}$$

$$b_R = \frac{\tilde{m}_{R,E(S)}}{1-\bar{m}_{R,E(k+1)}} \tag{14}$$

where b_l donates for degree of confidence of the evaluation results, b_R donates for degree of confidence of uncertainty of the evaluation results. $m_{l,E(k)}$, $\bar{m}_{R,E(k)}$, $\tilde{m}_{R,E(k)}$ are results of the fusion of the first k rules, and stipulate that $m_{l,E(1)} = m_{l,1}$, $\bar{m}_{R,E(1)} = \bar{m}_{R,1}$, $\tilde{m}_{R,E(1)} = \tilde{m}_{R,1}$.

The conversion of input information of different forms. The conversion of input information is to convert input information into a reliability data structure, and calculate the matching degree of input to the premise condition of rules, the input forms are as Eq.15

$$(x_1, e_1) \wedge (x_2, e_2) \wedge \mathbf{L} \wedge (x_M, e_M) \tag{15}$$

$e_i (i = 1, 2, \mathbf{L}, M)$ donates for the degree of confidence set to input, reflecting the uncertainty of the other i input, M is the number of inputs.

Using fuzzy semantic value to describe quantitative input information. For the evaluation system, evaluation index mostly has the following forms of quantitative information(1)deterministic numerical;(2)closed interval;(3)triangular fuzzy number;(4)the trapezoidal fuzzy number. In order to convert the input information x_i of the above form into matching degree $a_{i,j}$ relative to the fuzzy reference value $A_{i,j}$, calculation formula is as Eq.16

$$a_{i,j} = \frac{j(x_i, a_{i,j}) e_i}{\sum_{j=1}^{J_i} j(x_i, a_{i,j})} \tag{16}$$

$a_{i,j} \in [0,1]$, $j(x_i, a_{i,j})$ is the similar degree of x_i and $A_{i,j}$, called similar function. The selection of j is related to index type, specific discussion see the literature [1-3]

Use the subjective decision to describe the qualitative input information.The degree of confidence $a_{i,j}$ of input relative reference $A_{i,j}$ is given directly by the decision makers (or experts) according to the subjective. For example, if $e_{i,j}$ is the degree of confidence relative to $A_{i,j}$ which is the experts offer for qualitative input information, then $a_{i,j} = e_{i,j}$.

The evaluation model based on RIMER

The selection of evaluation index. Through statistical analysis and query converter transformer current rules, analysis of the experts' opinions and inducing 14 low-level evaluation indexes of converter transformer reflecting running state, as input information of the evaluation model, as shown in Fig.1

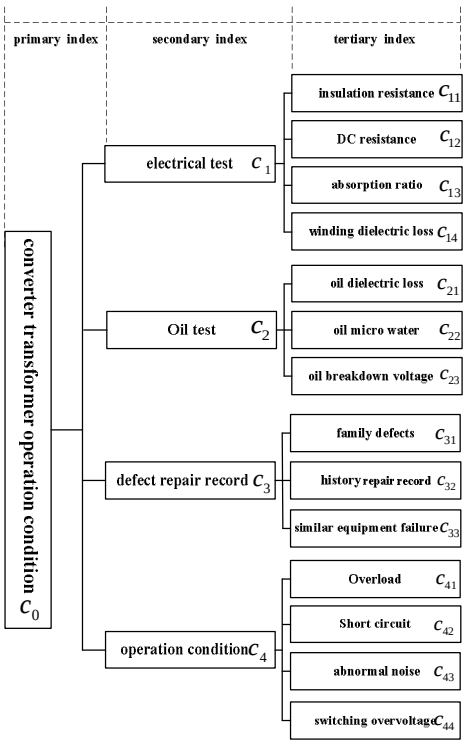

Fig.1 Evaluation indexes of converter transformer condition

The evaluation indexes are mainly divided into 4 categories such as electrical test c_1, oil test c_2, defect repair records c_3 and operation conditions c_4. The evaluation indexes from aspects of the equipment itself, test and operation comprehensively reflecting the service life of converter transformer such as insulation aging condition, internal health, electrical or mechanical properties, and from vertical and horizontal aspects to analyse the problems left over by history and defects of the family. On account of that the parameters reflecting the running state of the converter transformer are so many. In order to analyse it conveniently, this paper uses the index system of the tower structure, which can more easily grasp the relationship between the various indicators. The established status of the evaluation index system is a hierarchy structure of three layers, including 1 primary evaluation indexes, 4 secondary evaluation indexes and 14 tertiary evaluation indexes.

The conversion input information. For quantitative test index information, using relative deterioration degree with membership function method to deal with it. Relative deterioration degree is a scope for quantitative indexes of [0,1],to characterize the deterioration degree of transformer current running status compared to the fault status. The specific calculation process see literature[4]. According to the degree of degradation, and then combining with the relevant rules and expert experience to determine electrical triangle and half trapezoid distribution function for three kinds of state level (good, average, bad) fuzzy boundary range, establishing relative deterioration degree grade of membership function for each state. The final results are presented as membership degree set $R_i = [r_{i1}, r_{i2}, r_{i3}]$, $r_{ij} \in [0,1]$ ($j = 1,2,3$) is representing membership degree of three kinds of state level (Good, Average, Bad) respectively. The specific calculation process see literature [5].

Using expert scoring method to deal with qualitative information such as defect repair record and operation condition information. First using expert survey form, that is, gives the evaluation objects and evaluation index according to the survey, by the experts estimate evaluation matrix, then combined with analytic hierarchy process (AHP), calculating membership degree of each the final indexes. The specific calculation process see literature [6-7].Transformation of input information degree of confidence is to transform the input information into confidence data structure. And the input form corresponding to evaluation index is Eq.17

$$(x_1, e_1) \wedge (x_2, e_2) \wedge (x_3, e_3) \tag{17}$$

x_i donates for the precondition of input attributes, e_i donates for degree of confidence of x_i ,taking

biggest two degree of confidence of the premise properties as input information. Such as insulation resistance is 1235.6 MΩ ,after relative deterioration degree and membership degree calculation ,the results are R_{11}=[0.74,0.25,0].The input information of insulation resistance is (Good,0.74)∧(Average,0.25), simplified as c_{11}=(0.74,0.25,0).

Establishing the initial belief rule base. Establishing an initial belief rule base according to the evaluation index premise attribute reference set by the above and expert experience. Assuming that the rules weights in rule base are equal, the relative weight of the premise of rules are also equal, namely $q_k = q_l\ (k \neq l), d_{k2} = d_{k1} = \cdots = d_{kT_k}$

The initial belief rule base includes 14 tertiary evaluation indexes, 4 secondary evaluation indexes and 1 primary evaluation index. Tertiary evaluation index is divided into three grades: good, average and bad. Primary evaluation index and secondary evaluation index is also divided into three levels: normal, warning and urgent. The initial belief rule base has 297 rules. Limited to the space, listing part of them, as Table 1.

Table 1 The initial belief rule base

ID	Premise condition	Evaluation result	ID	Premise condition	Evaluation result
R_1	c_{11}=A,c_{12}=A,c_{13}=A,c_{14}=A	c_1={(Nor.,1),(War.,0),(Urg.,0)}	R_6	c_{11}=A,c_{12}=A,c_{13}=B,c_{14}=C	c_1={(Nor.,0.1),(War.,0.3),(Urg.,0.6)}
R_2	c_{11}=A,c_{12}=A,c_{13}=A,c_{14}=B	c_1={(Nor.,1),(War.,0),(Urg.,0)}	R_7	c_{11}=A,c_{12}=A,c_{13}=C,c_{14}=A	c_1={(Nor.,0.2),(War.,0.4),(Urg.,0.4)}
R_3	c_{11}=A,c_{12}=A,c_{13}=A,c_{14}=C	c_1={(Nor.,0.2),(War.,0.5),(Urg.,0.3)}	R_8	c_{11}=A,c_{12}=A,c_{13}=C,c_{14}=B	c_1={(Nor.,0.1),(War.,0.2),(Urg.,0.7)}
R_4	c_{11}=A,c_{12}=A,c_{13}=B,c_{14}=A	c_1={(Nor.,0.7),(War.,0.3),(Urg.,0)}	R_9	c_{11}=A,c_{12}=A,c_{13}=C,c_{14}=C	c_1={(Nor,0),(War,0.2),(Urg,0.8)}
R_5	c_{11}=A,c_{12}=A,c_{13}=B,c_{14}=B	c_1={(Nor.,0.4),(War.,0.6),(Urg.,0)}	…	…	…

A denotes for Good, B denotes for Average, C denotes for Bad, Nor. denotes for Normal, War. denotes for Warning, Urg. denotes for Urgent.

Case study

This paper studies a converter transformer of a 500kV convertor station. According to consulting the history records of maintenance, we find that there was a small defect record of the transformer few years ago and there is no family defects or similar equipment failure. In 2013 and 2015, there is a short-term overload respectively. Two short circuit have occurred in 2014 and there is no abnormal noise or operating over voltage. In a preventive test, the measured insulation resistance is more than 10000 which is similar to the last test, the absorption ratio is 1.25, the oil dielectric loss is 0.153, the maximum change rate of winding DC resistance phase is 1.35%, the winding dielectric loss is 0.32, the oil micro water is 15.6mg/l, and the oil breakdown voltage is 48kv.

After calculating the relative deterioration degree and membership degree of the evaluation index, and then the reliability is converted, the calculation results are as follows:c_{11}=(1,0,0), c_{12}=(1,0,0), c_{13}=(0.44,0.56,0),c_{14}=(0.38,0.62,0),c_{21}=(1,0,0),c_{22}=(0.88,0.11,0),c_{23}=(0.75,0.24,0),c_{31}=(1,0,0),c_{32}=(1,0,0),c_{33}=(1,0,0),c_{41}=(0.33,0.66,0) c_{42}=(0.45,0.55,0),c_{43}=(1,0,0),c_{44}=(1,0,0)。

First, calculating the electrical test c_1, and c_{11}=(1,0,0),c_{12}=(1,0,0),c_{13}=(0.44,0.56,0),c_{14}=(0.38, 0.62,0) are known. The input activates the rule R_1, R_2, R_4, R_5 in belief rule base, according to the Eq.2,Eq.3 and Eq.16, w_1=0.12, w_2=0.19, w_4=0.26, w_5=0.43, m_1=1, m_2=1, m_4=1, m_5=1. According to the Eq.5~Eq.8,(m_{11} , m_{21} , m_{31} , m_{R1} , $\bar{m}_{R1}$, $\tilde{m}_{R1}$)=(0.08,0.04, 0,0.88,0.88,0),(m_{12} , m_{22} , m_{32} , m_{R2} , $\bar{m}_{R2}$, $\tilde{m}_{R2}$)=(0.07,0.12,0,0.81,0.81,0),(m_{14} , m_{24} , m_{34} , m_{R4} $\bar{m}_{R4}$, $\tilde{m}_{R4}$)=(0.12,0.14, 0,0.74,0.74,0),(m_{15} , m_{25} , m_{35} , m_{R5} , $\bar{m}_{R5}$, $\tilde{m}_{R5}$)=(0.15, 0.28,0,0.57,0.57,0). According to the Eq.9~Eq.14, c_1(Normal, Warning, Urgent) =(0.53, 0.47, 0).

Similarly, followed by calculation of the oil test c_2, defect repair record c_3 and operating condition of the c_4, and the value of converter transformer operation condition c_0. In the calculation process from the bottom, the index is upper, the number of rules activated is more, so in the MATLAB programming the above algorithm is achieved according to the Eq.2~Eq.16. The results are as follows: c_2=(0.84,0.15,0), c_3=(1,0,0), c_4=(0.41,0.58,0), c_0= (0.49,0.51,0).From the calculation results, it can be seen that the running state of converter transformer is between "Normal" and "Warning", and the degree of confidence of the "Warning" is higher. Among them, degree of confidence of the " Warning" in the evaluation results of electrical test c_1 and operation condition c_4 are both high, which should be paid attention to. The actual situation is that the converter transformer has ran for a long time and there were twice over load, leading to partial aging of internal insulation, the overall status is safety, and the transformer can continue to run, but it needs to be observed, which is consistent with the evaluation result.

Conclusions

The approach of converter transformer condition evaluation based on the belief rule base inference methodology and evidence reasoning (RIMER) is a comprehensive evaluation method which combine qualitative with quantitative and calculation results with expert experience. Although the evaluation index type is of diversification and evaluation information is incomplete, this method provides a probability distribution of the overall equipment operation status. It better solved the problem to evaluate converter transformer condition accurately due to the information uncertainty lead by the combination of quantitative index and qualitative index.

The case shows that the converter transformer condition evaluation approach based on the belief rule base inference methodology and evidence reasoning (RIMER) can well reflect the actual running status of equipment and can provide the scientific decision-making of maintenance for the next step. How to establish a belief rule base appropriately and confirm values of premise weights precisely is the key point to this evaluation approach and also the future research direction of the method.

References

[1] Yang Jianbo. European Journal of Operational Research ,2001, 131(1):31-61.

[2] Bustince H, Burillo P. Fuzzy Sets and Systems,2000. 113: 205-219.

[3] Chen S M, Hsiao W H. Fuzzy Sets and Systems, 2000, 113: 185-203.

[4] Viasne S, Wets G, Vanthienen J. Fuzzy Sets and Systems,2000, 113: 253-265.

[5] Wang Qian, Study of the Comprehensive Assessment Method for The Power Transformer Condition in service with Fuzzy theory[D]. Chongqing University, 2005. (In Chinese)

[6] Zhang Deng, Research on Condition Assessment Method for Power Transformer[D]. Huazhong University of Science and Technology, 2013. (In Chinese)

[7] Zhang Biao, Wang Yuhong, Li Xingyuan, etc.High Voltage Apparatus, 2015, 51, (9), 60-65. (In Chinese)