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A Condition Assessment Model of Oil-immersed Transformers Using Cloud and Matter Element Integrated Method

***Abstract**. High voltage oil-immersed transformers are the most important components in the power system. If there is a potential fault in the transformer it may cause a power failure even a catastrophe. Therefore, it is important to assess the condition of the transformer accurately and to make some relative maintenance to minimize the risk of premature failure. However, condition assessment of transformers can be considered as a multiple-attribute decision-making (MADM) problem which is full of uncertain, fuzzy and randomness information. Aiming at this intricate problem, this paper presents a cloud and matter element integrated approach for assessing the condition of transformers. An assessing index system is established, which includes dissolved gas analysis (DGA), electrical testing and oil testing. An integrated model based on matter element approach and cloud approach is applied to assess the condition of the transformer. Cases study show that the proposed approach is practical and effective. The assessing result can be regarded as a useful suggestion to condition based maintenance of high voltage oil-immersed transformers.*

***Streszczenie.** W artykule przedstawiono metodę oceny stanu technicznego transformatora olejowego, opartą na analizie elementów chmury oraz tzw. Matter-Element Analysis. Opracowany został zintegrowany model oraz wskaźnik szacujący stan transformatora, uwzględniający czynniki takie jak: analiza rozpuszczonych gazów (DGA), testy elektryczne i olejowe. Przeprowadzone badania potwierdziły skuteczność metody. (**Ocena stanu technicznego transformatora olejowego na podstawie modelu szacunkowego – wykorzystanie metod elementów chmury i materii**).*

Keywords: Oil-immersed transformers; condition assessment; MADM; cloud model; cloud and matter element integrated.
Słowa kluczowe: transformator olejowy, szacowanie warunktów, MADM, model chmurowy, integracja elementów chmury i materii.

Introduction

The safety of electrical equipment plays an important role in the power system security. As the key equipment in the power system, the operational condition of high voltage oil-immersed transformers is closely related to the reliability of the grid. Failures of the transformer may cause great financial losses and even arouse a catastrophic outage. Therefore, it is necessary to make an accurate assessment of transformer condition [1], [2]. The advantages of condition assessment are not only to reduce expenses, but also to reduce the risk of premature failure. For example, it helps detect and eliminate transformer incipient faults before it deteriorates to a severe condition. It can also offer an improved approach to change the maintenance strategy and the strategy can avoid the disadvantage of the regular overhaul in excess or shortage condition [3], [4].

Recently, since DGA is a non-intrusive technique for detecting incipient faults of transformers, fault diagnosis of oil-immersed transformers mainly focuses on DGA. Approaches such as SVMs Modelling Method [5], Maximal margin classifiers [6], ANN [7, 8], Ratio methods [9] and support vector machine with genetic algorithm [10] are applied to evaluate the condition of power transformer. Besides, partial discharge [11, 12] is also an effective way to evaluate the insulation condition of transformers. However, only one or two techniques mentioned above are not enough to precisely assess the condition of transformer because they can only estimate the transformer in good or fault condition. In fact, a transformer is often in the condition between them. Article [13] represents a fuzzy and evidential reasoning integrated model for condition assessment of transformer but did not take randomness into account. Actually, the attention value of its condition characteristics needs experts to determine and the boundary limits of the value have some ambiguity and randomness. Besides, different indexes sometimes reflect the different aspects, which is easy to generate the phenomenon of information overlapping. Therefore, the assessing result sometimes is not satisfactory when resolving condition assessment problem of transformers [14].

To deal with these problems, in this paper, an assessing model, including DGA data, electricity testing data and oil testing data, is established as the assessing model in the second section. A synthetic cloud and matter element model is presented to facilitate the assessing process in the third section. Advantages are obtained because the matter element theory is capable to solve the contradiction caused by the multi index evaluation and the cloud model is an effective tool for describing the random and fuzzy properties of transformers. In the fourth section, two cases are studied to demonstrate how to use the approach to solve assessing problems.

Framework of transformer condition assessment
The assessing system of transformers

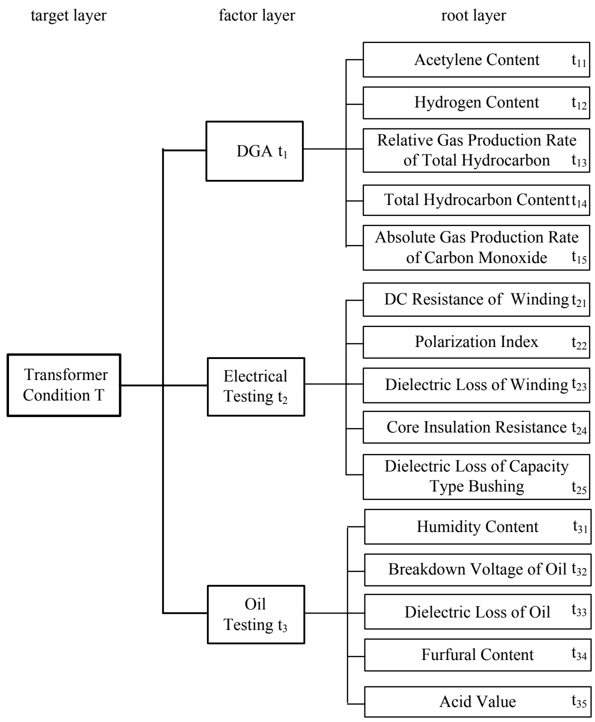

Fig.1. Assessing index system

Condition assessment of a transformer is considered as a multi-index assessing problem. Whether an appropriate index system is established or not will directly impact on the accuracy of the evaluation. The diagnostic mechanism of a transformer is complicated because there are a lot of indexes reflecting the condition of the transformer. However, all the indexes shall not be selected into the index system because some indexes reflect the same condition of transformer part. For example, as the same as the polarization index, the absorption ratio influences the condition of the winging. Furthermore, if too many indexes are selected to the index system, it will cause low feasibility for engineering application. By contrast, little indexes system cannot reflect the condition of transformer accurately. Consequently, in order to achieve an appropriate evaluation system, preventive tests and the mature detective means at present are selected to the index system [15] – [17].

As shown in Fig. 1, a three layers index system named the tree model is established. The left layer named the target layer is the evaluation outcome of transformer condition. The middle layer called the factor layer describes different parts of transformer. The right layer named the root layer is a partition of the factor layer. The assessing model is suitable for condition assessment of high voltage oil-immersed transformers (voltage: 110kV, 220kV and 500kV).

Data Preprocessing

Since different indexes have different dimension or magnitude, the data preprocessing of indexes must be done before condition assessment.

Generally, assuming that x_{i0} is the optimal value or the rating value that given by a product. x_{i1} is the worst value or the attentive value which is decided by transformer tests and operation standards. t_{ij} is the field testing data. The normalization process can be defined based on linear interpolation methods as follows:

The indexes, which values are the larger the better, such as insulation resistance of core and polarization index, are preprocessed by the following formula.

(1) $$y_{ij} = \begin{cases} 0 & x_{ij} \ge x_{i0} \\ (x_{i0} - t_{ij})/(x_{io} - x_{i1}), & x_{i1} < t_{ij} < x_{i0} \\ 1 & x_{ij} \le x_{i1} \end{cases}$$

where: x_{i0} –optimal value, x_{i1} –attentive value, t_{ij} –a testing data of the index system

The indexes, which values are the smaller the better, such as acetylene content and furfural content, are processed by the following formula.

(2) $$y_{ij} = \begin{cases} 1 & x_{ij} \ge x_{i1} \\ (t_{ij} - x_{io})/(x_{i1} - x_{i0}), & x_{i0} < t_{ij} < x_{i1} \\ 0 & x_{ij} \le x_{i0} \end{cases}$$

where: x_{i0} –optimal value, x_{i1} –attentive value, t_{ij} –a testing data of the index system.

Table 1. Relations between deterioration degrees and states

Condition	Good	Normal	Attentive	Poor	Serious
Maintenance	post repair	normal cycle	prior	sooner	immediate

In the assessing grades, g_n is defined as the evaluation grade (n = 1, …, N, N = 5 in this paper). The assessing grades are related to maintenance purposes and the set of distinct grades can be defined as (3). The relationships between the grades and maintenance strategy are shown in Table 1.

(3) $$g = \{good, normal, attendtive, poor, serious\}$$

where: g – grades.

A Cloud and Matter element integrated method

Cloud method

Presently, cloud model is a practical approach to handle problems with fuzziness and randomness [18]. The main concept of the cloud model is shown in [19]–[20].

The advantage of the cloud model is using stable trend values to describe the membership degree of the concept set. In other words, the cloud model uses a fluctuant value to describe randomness of the concept set. When qualitative concept T is given, the certainty degree of x belonging to T, which is called membership degree, is an undulated value in a certain range rather than a fixed number. In this way, the cloud model can effectively integrate the randomness and fuzziness of concepts and describe the overall quantitative property of a concept by the three numerical characteristics as follows.

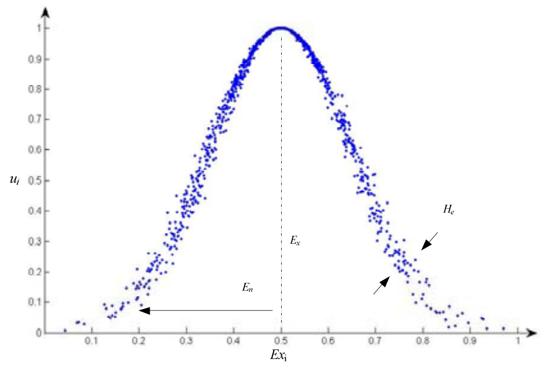

Fig.2. A normal cloud model

Suppose that U is the universe of discourse and B is a qualitative concept. Let x be a random instantiation of concept B, if x ~ N (Ex, En'^2), En'~ (En, He^2), the degree value of x belonging to concept B can be calculated by (3) [20].

(3) $$u_i = e^{-(x_i - Ex_i)^2/2En'^2_i}$$

where: u_i– the membership degree of the ith index, x_i –a random instantiation of the ith index, Ex_i – Ex of the ith index.

The distribution of x in the universe U is called as a normal cloud. For example, if three numerical characteristics are given, Ex = 0.5, En = 0.15, He = 0.01, N = 1000, concept B can be described as Fig. 2.

Matter element method

The matter element method studies law and resolution of the conflict problems from both qualitative and quantitative point of view [21], [22]. The concept of matter element is to provide a new way for classification and pattern recognition of things [9].

Suppose that the name of a matter is N, one of the characteristics of the matter named c and the value of c which is called v, a matter element in extension theory can be depicted as R = (N, c, v). N, c, and v are the three necessary elements of the matter element. For example, R_x = (DGA, H_2, 22 μL/L) and R_z = (transformer, condition, good) are two simple matter element. In addition, assuming $C = \{c_1, c_2, ..., c_n\}$ is a characteristic vector and $V = \{v_1, v_2, ..., v_n\}$ is a value vector of C, the name of a matter is defined by N. Finally, a multi-dimensional matter element can be described as (4).

(4) $$R=\begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix}$$

where: R – a matter, N –the name of a matter, C,V –vectors.

Cloud Matter element method

Suppose that H_h (h = 1, 2, 3) is the hth factor in the factor layer and this factor can be subdivided into n indexes. Let C_n be all the indexes of H_h and $v_{pi} \in (a_{pi}, b_{pi})(i = 1, 2, \ldots, n)$ be the intervals of the pth grade of ith index. By using the advantage of cloud model to solve the uncertain problem, the value of V_{pi} is replaced by (Ex_{pi}, En_{pi}, He_{pi}). As each index is subdivided into five grades (p = 1, 2, …, 5), the cloud matter element can be shown as R_h.

(5) $$R_h=\begin{bmatrix} H_h & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix}=\begin{bmatrix} H_h & c_1 & \langle a_{p1},b_{p1}\rangle \\ & c_2 & \langle a_{p2},b_{p2}\rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn},b_{pn}\rangle \end{bmatrix}$$
$$=\begin{bmatrix} H_h & c_{h1} & (Ex_{p1},En_{p1},He_{p1}) \\ & c_{h2} & (Ex_{p2},En_{p2},He_{p2}) \\ & \vdots & \vdots \\ & c_{hn} & (Ex_{pn},En_{pn},He_{pn}) \end{bmatrix}$$

where: R_h –the cloud matter element, H_h –the name of a matter, Ex_{pi}, En_{pi}, He_{pi} (i=1, 2, …, n)– the $p$ith value of Ex, En, He

After the integrated model is established, the next step is to get the three numeric characteristics of the cloud model. Assuming the range of five levels defined as f_1 (0, a], f_2 (a, b], f_3 (b, c], f_4 (c, d), f_5 (d, e] (e, $+\infty$). The three digital characteristics of cloud are calculated in Tab.2. In this paper, 0.01 is the value assigned to q by experience of experts. Therefore, the numeric characteristics of cloud calculated by Table 2 are applied to generate single indicator normal cloud models by (3). The cloud model is shown in figure 3. In the figure, the horizontal axis is the value of the index data y_{ij} and the vertical axis is the membership value.

Correlations between an index value y_{ij} and the cloud grades are calculated by following steps. First, consider the value y_{ij} as a cloud droplet. Then a random number En'_{pi} belonging to normal distribution is generated so that the expected value is En_{pi} and standard deviation is He_{pi}. Finally, the correlation of y_{ij} belonging to the kth grade is obtained by the (6).

(6) $$C_k(V_{pi})=\exp\left(-\frac{(y_{ij}-Ex_{pi})^2}{2(En'_{pi})^2}\right)$$

where: $C_k(V_{pi})$ – the correlation of y_{ij} belonging to the kth grade, Ex_{pi}, En_{pi}, He_{pi}– the $p$ith index value of Ex, En, He.

$C_k(V_{pi})$ is the correlation between the ith index and the kth state level. It describes the ownership degrees of indexes belong to each assessment level. However, the correlation between y_{ij} and the condition cloud is not a fixed number but a fluctuant value. Thus, after S (S = 1000) times of generation by the process, the average value of the correlation can be obtained by (7).

(7) $$C_k(V_{pi})_{final}=\sum_{i=1}^{n}C_k(V_{pi})_i \Big/ S$$

where: $C_k(V_{pi})_{final}$ – the addition of $C_k(V_{pi})$, $C_k(V_{pi})$ – the correlation of y_{ij} belonging to the kth grade, S – times of generation.

Obviously, the larger its value is, the more attributes it has in level k. By the same means, the correlations between each index and all the state levels can be obtained and they are recorded by a relationship matrix $R[m]$ $[K]$. Therefore, a certain relationship between the mth Index and the kth cloud is described by the mth matrix row and the kth matrix column of the matrix $R[m]$ $[K]$.

Table 2. Characteristic value of the integrated model

Grade	(f_1)	(f_2)	(f_3)	(f_4)	(f_5)
Ex	Ex_1=0	En_2=(a+b)/2	En_3=(b+c)/2	En_4=(c+d)/2	En_5=d
En	En_1=(Ex_2-Ex_1)/6	En_2=(Ex_2-Ex_1)/6	En_3=(Ex_3-Ex_2)/6	En_4=(Ex_4-Ex_3)/6	En_5=(Ex_5-Ex_4)/6
He	q	q	q	q	q

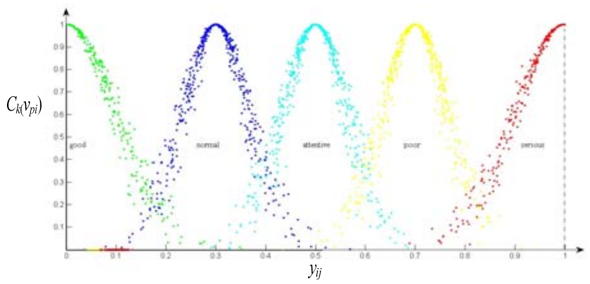

Fig.3. Membership degree of cloud model

Process of transformer condition assessment

Recently, subjective weighting is a method by which experts get the original data mainly according to the experience and they can reasonably determine the weight of each index according to actual condition. Therefore, in this paper, some questionnaire surveys are given to five experts to decide the relative importance degree of each index in the same factor level. After that, a subjective approach called analytic hierarchy process (AHP) is applied to determine weights [18]. The weight information is shown in Table 3. If the measurement of the ith index is missing, revised weight information is calculated by (8).

(8) $$\omega_{kj}^{(1)}=\frac{1}{1-\omega_{ki}^{(0)}}\omega_{kj}^{(0)} \qquad (j\neq i)$$

where: $\omega_{kj}^{(0)}$ - the original weight of the jth index in the kth factor, $\omega_{kj}^{(1)}$ - the revised weight of the jth index in the kth factor, $\omega_{ki}^{(0)}$ - the original weight of the missing ith index in the kth factor.

Table 3. Weights of factors and indices

Factor	Weights(W)	Corresponding index weights(w_j)
t_1	0.4176	0.3519 0.1174 0.2376 0.1758 0.1174
t_2	0.3705	0.2237 0.1429 0.1429 0.3050 0.1855
t_3	0.2119	0.1821 0.1821 0.1630 0.3782 0.0947

By synthesizing the weight matrix of the indexes and the relationship matrix $R_{m\times k}$, the evaluation result of the factor grade can be obtained by (9).

(9) $$K_j(P)=w_j\times R_{m\times k}$$

(10) $$G=W\times K_j(P)$$

where: w_j –the corresponding index weights in the jth factor, $R_{m\times k}$ –the relationship between the mth index (in the jth factor) and k assessing grades, obtained by the relationship matrix $R[m]$ $[K]$, W – the weights of factors, $K_j(P)$ –the relationship between the jth factor and k assessing grades, G – total condition of transformer.

K_j (P) is the relationship between the relationship between the jth factor and k assessing grades. It is used for describing the condition of each factor. By synthesizing the weight of the factors and K_j (P), the total condition of transformer G can be calculated as (10).

The principle of maximal correlation can be used to make a decision for transformers condition assessment. Finally, a process of evaluation is shown in Fig. 4

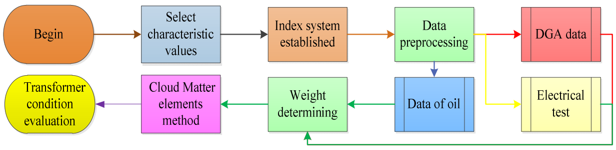

Fig.4. Process of transformer condition assessment

Experimental Results

Testing Example 1

The preventative testing data, which are acquired from a 220kV transformer in an electric company in China, are shown in Table 4.

With regard to the preliminary test data in Table 4, total hydrocarbon content is 150.6 (μL/L) and 442.7 (μL/L). Besides, its absolute producing rate is 7.32 (mL/d) and the absolute producing rate of carbon monoxide (CO) is 15.3 (mL/d) by calculating [17]. Firstly, (1) and (2) are used for obtaining the normalized matrix Y_{ij} of each index.

Table 4. Preventive test results of the transformer.

Testing items	Testing dates	
	2008-08-13	2009-08-27
Hydrogen content (unit×10^{-6})	26.70	38.20
Methane content (unit×10^{-6})	33.90	81.70
Ethane content (unit × 10^{-6})	19.2	46.00
Ethene content (unit × 10^{-6})	97.5	164.30
Acetylene content (unit × 10^{-6})	0	0.1
Carbon monoxide content (unit × 10^{-6})	48.50	95.60
Total hydrocarbon content (unit × 10^{-6})	150.6	442.7
DC resistance of winding (%)	0.67	0.72
Polarization Index	1.75	1.66
Dielectric loss of winding (%)	0.34	0.35
Insulation resistance of core	1100	100
Dielectric loss of capacity type bushing (%)	0.32	0.33
Humidity content (mg/L)	21.5	22.3
Breakdown voltage of oil (kV)	50.00	48.00
Dielectric loss of oil (%)	2.42	3.00
Furfural content (mg/L)	0.02	0.05
Acid value (mg(KOH)/g)	0.014	0.026

$$(11)\qquad Y_{ij}=\begin{bmatrix}0.0200 & 0.2547 & 1.0000 & 1.0000 & 0.1530\\ 0.3600 & 0.6800 & 0.4375 & 0.9990 & 0.4125\\ 0.8920 & 0.6286 & 0.0825 & 0.0500 & 0.2600\end{bmatrix}$$

After the digital characteristics are calculated by the formulas shown in Table 3, the clouds model is generated by (4). By using the information of (11), formula (6) and (7) are used for obtaining the correlation between the indexes and the clouds and the results can be obtained in Table 5.

According to Table 5, by using the cloud matter element method process and (9), a factor condition matrix $G(H)$ is obtained in (12).

$$(12)\qquad G(H)=\begin{bmatrix}0.4048 & 0.1818 & 0.0002 & 0.0000 & 0.4134\\ 0.0000 & 0.2816 & 0.2742 & 0.1392 & 0.3050\\ 0.5391 & 0.0966 & 0.0397 & 0.1527 & 0.1720\end{bmatrix}$$

To obtain the condition assessment result of the transformer, (10) is applied for synthesizing the factor conditional information which is show in (12). The condition of the transformer G is shown in (13).

Table 5. Correlation between indexes and assessing grades

Correlation degrees	Assessing grades for indexes				
	g_1	g_2	g_3	g_4	g_5
t_{11}	0.9998	0.0002	0.0000	0.0000	0.0000
t_{12}	0.0009	0.9977	0.0014	0.0000	0.0000
t_{13}	0.0000	0.0000	0.0000	0.0000	1.0000
t_{14}	0.0000	0.0000	0.0000	0.0000	1.0000
t_{15}	0.4498	0.5502	0.0000	0.0000	0.0000
t_{21}	0.0000	0.8579	0.1421	0.0000	0.0000
t_{22}	0.0000	0.0000	0.0268	0.9732	0.0000
t_{23}	0.0000	0.1563	0.8431	0.0006	0.0000
t_{24}	0.0000	0.0000	0.0000	0.0000	1.0000
t_{25}	0.0000	0.3631	0.6368	0.0001	0.0000
t_{31}	0.0000	0.0000	0.0000	0.0555	0.9445
t_{32}	0.0000	0.0000	0.2167	0.7833	0.0000
t_{33}	0.0000	0.0000	0.0012	0.9976	0.0012
t_{34}	0.9988	0.0012	0.0000	0.0000	0.0000
t_{35}	0.0006	0.9976	0.0018	0.0000	0.0000

$$(13)\qquad G=[0.2832\ 0.2007\ 0.1101\ 0.0840\ 0.3221]$$

According to (13), the conclusion can be drawn as grade g_5 and the result indicates that the transformer is in a serious condition. Maintenance and testing should be done to transformer immediately. By further analyses, total hydrocarbon content, total hydrocarbon gas production rate and core insulation resistance preponderate over the attention value. It may be a local overheating fault in the transformer. Actually, the result is reasonable and the factual condition of the transformer was that a nail is loose. This haphazard leaded to a juncture between core and clamping, which caused the short circuit overheating fault. In conclusion, the result demonstrates that the proposed is a reliable tool for condition assessment of transformers.

Testing Example 2

According to the article [13], the calculation result by using the fuzzy evidence method is shown in (14).

$$(14)\qquad G_1=[0.0011\ 0.2445\ 0.3432\ 0.3472\ 0.0336]$$

In this paper, in order to testify the correctness of the cloud matter element method, there should be a comparison between two methods. Therefore, by using the same method presented in Testing Example 1, the assignment matrix is acquired and shown in (15).

$$(15)\qquad G(H)=\begin{bmatrix}0.0017 & 0.1137 & 0.2666 & 0.6180 & 0.0000\\ 0.0001 & 0.4618 & 0.1911 & 0.1636 & 0.1835\\ 0.0000 & 0.4246 & 0.1349 & 0.3742 & 0.0663\end{bmatrix}$$

With the same computational method, a judgment matrix is obtained in (16).

(16) $$G_2 = [0.0007\ 0.3146\ 0.2079\ 0.3939\ 0.0829]$$

According to the calculation, obviously, the overall condition of transformer is in the condition of g_4 and the maintenance strategy is that maintenance and testing should be done later to the transformer. Actually, the condition of the transformer was that the sealing between the top of the oil tank and bushing coupler was not tight, which caused the transformer insulation to be moist.

It is obvious that the evidences supported by grades of g_3 and g_4 are proximally the same and hard to distinguish efficiently in (14). Therefore, this situation often leads to a mistake assessment of the condition. By contrast, as the proposed method is implemented in the evaluation framework, the result of condition assessment is clear in (16) and the rate of the misevaluation mentioned above is inclined to a little probability. Therefore, the result demonstrates the reliable property of the proposed method and its potential to treat uncertainties and randomness in MADM problems.

Conclusions

This study represents an integrated approach to condition assessment of high voltage transformers (110kV, 220kV and 500kV). The results of the reported work can be summarized as follows:

(1) The paper established an index system (including the DGA, electrical testing, and oil testing data) of oil-immersed transformers based on the related standards and some experience of experts. The assessing result demonstrates that the index system is a reliable model for condition assessment.

(2) A cloud and matter element integrated model is proposed. Through the construction of membership cloud model, the subjectivity and arbitrariness of the membership function are decreased.

(3) With the assessing process, the comprehensive assessment of transformers is realized and related maintenance strategies are given. The cases study show that the proposed method is an efficient tool to assess the condition of the transformer.

(4) Some qualitative indexes and new tests should be added into the model, such as previous operation history index and the on-load tap changer test. Therefore, there are still some limitations in the proposed model.

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