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The Lean Closed Loop Management of Transformer Operation in Low Voltage Distribution Network

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ABSTRACT The management of the distribution network transformers' operation (DNTO) has become a popular and efficient way for the power grid companies to enhance the efficiency of operation. However, the current method which is measured by a single index, is impossible to effectively and scientifically measure the DNTO and guide the management of the DNTO. In the management of the DNTO, the lean closed-loop management method is useful, but there are some key issues to be solved. This paper first proposes a multiindex system to define the DNTO to solve the first issue, which is the one-sidedness of a single index. Then the improved fuzzy comprehensive evaluation constructing by the triangular fuzzy number (TFN) and the relative similarity relation (RSR) is proposed to overall measure the DNTO for the second issue, which is the one-sidedness of a single comprehensive method. Besides, the relations among evaluation indexes are mined from related indexes to build the critical reference value (CRE) for the third issue, which is the current method can not find the defects of the DNTO. And, the Six Sigma management strategy is adopted to optimize the management process of the DNTO and form effective closed-loop management. Finally, both case studies are conducted to demonstrate that the proposed methods are effective.

INDEX TERMS Multiindex, triangular fuzzy number, critical reference value, six sigma management strategy.

I. INTRODUCTION

The economic operation of transformers plays an essential role in the operation management of power grid companies. Compared with some transformers in the high voltage level network, the operation of the distribution network transformers is relatively complex and involves many factors. Traditional evaluation can not adequately measure the economics of the distribution network transformers' operation. There are two main traditional ways to measure the economics of distribution network transformers' operation:

1) The data collation can record the process of the DNTO, and the economics of DNTO can be measured by a single index, which is the radiation-regional power loss rate of the transformer.

2) The economics of DNTO is measured by the average load rate, which is usually defined as 80%.

However, there are two problems in the above approaches.

1) The distribution network is complex, involving not only a large number of equipment factors but also human factors, so the radiation-regional power loss rate of the transformer can not fully reflect the economics of DNTO.

2) The average load rate is not suitable for the economic evaluation of the DNTO, because there is a significant fluctuation of load in the distribution network area and the vast difference between the peak and valley values of load.

Due to the lack of unified standards, the DNTO has gradually become the weak link in the operation of the power grid. How to evaluate the economics of DNTO and how to manage the transfomers have become important problems to be solved urgently.

The economic factors of the DNTO involve not only the transformer itself but also the equipments in its radiation area.

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The feeder line, the reactive power compensation device, the metering device, and the human factor influence the economics of the DNTO, so we must consider all factors to elevate and manage the DNTO which can be considered as a distribution network. With the improvement of power grid technology, the number of measurement equipments is increasing, which are installed at distribution lines and transformers. The terminal data that can be input by the data system increases exponentially, and the big data of DNTO are gradually formed.

Recently, a large number of studies on distribution network data mainly focus on condition assessment, power loss rate calculation, etc. Kim *et al.* proposed the strategies to reconfigure the feeder, by using artificial neural networks with the mapping ability in the distribution network [1]. Queiroz and Lyra proposed an alternative loss estimation approach, which relies on the fundamental parameter for describing load variations in loss estimation [2]. Hung *et al.* proposed an improved analytical (IA) method to calculate the optimal size of four different DG types and a methodology to identify the best location for DG allocation [3]. Lee and Park proposed the optimal locator index, which is developed to determine the optimal locations systematically and effectively by the power loss sensitivities [4]. Nekooei *et al.* proposed a new approach using Harmony Search (HS) algorithm for placing Distributed Generators (DGs) in radial distribution systems [5]. Dashtaki and Haghifam proposed a new heuristic method for loss estimation of the low-voltage sector of a large scale distribution network faced by a scarcity of network data [6]. Jin *et al.* focused dynamic asset rating from a network perspective by proposing a dynamic network rating approach, which available for use with Dynamic asset rating are discussed and compared using measured load and weather data from a trial network area within Milton Keynes in the central area of the U.K [7]. Macedo *et al.* presented a mixed-integer second-order cone programming model to solve the optimal operation problem of radial distribution networks with energy storage [8]. The above literature [1]–[8] shows that the distribution network operation involves the aspects of formulation, so it is feasible to measure the economics of the DNTO by using big terminal data. However, when the big terminal data is applied to the DNTO evaluation and management, there are also some problems to be solved as following.

1) How to effectively use the big terminal data to establish the economic operation index system of DNTO?

2) How to use the index system mentioned above for effective evaluation?

3) How to effectively use the index system to analyze the shortcomings of the current DNTO rationally?

4) How to manage the DNTO effectively on the index system?

For the first problem, the big data have become the key link connecting all links of DNTO. The data index system of the DNTO with multi-dimensional and multi-index data is constructed, which reflects the whole process of the DNTO, improving the data management of the DNTO.

For the second problem, each basic algorithm puts forward different opinions and conclusions to understand and adapt to the DNTO from different perspectives. The TFN with the RSR is used to optimize the evaluation conclusion to avoid singleness.

For the third problem, the optimization vector space model quantitatively expresses that the process index is affected by human factors by calculating the cosine value of the angle between the data vector and the related index vector. Based on this, the CRE of the process indexes is sought, which finds the real deficiencies of the DNTO.

For the fourth problem, the Six Sigma management strategy DMAIC and PDCA are adopted to optimize the management process of the DNTO.

In order to prove the effectiveness of the proposed method, case studies are carried out in this paper. The results show that our method can evaluate and manage the economics of DNTO well on the premise of the big terminal data. The contributions of this paper are as follows.

1) The data index system of the DNTO is established.

2) The TFN with the RSR optimization are used to flexibly optimize the results of various evaluation algorithms and to evaluate the economics of the DNTO.

3) By using the CRE, the weak links of the DNTO are analyzed to make up for the shortcomings of traditional standard-setting deviating from the object with a better foundation.

4) Introducing the Six Sigma management strategy tool, DMAIC and PDCA, standardize and streamline the management of the DNTO.

The rest of this paper is organized as follows. In Section II, related work and certain basic theories are discussed. In Section III, the management of the DNTO method is proposed. In Section IV, study results are shown to verify the effectiveness of the proposed methods. Finally, Section V concludes this paper and offers further research work.

II. RELATED WORK

A. THE SINGULAR VALUE OPTIMIZATION

The singular value decomposition (SVD) is a critical matrix decomposition method in linear algebra and matrix theory, which is usually use in signal processing and statistics. Capozzoli *et al.* used singular value optimization in inverse electromagnetic scattering [9]. Howland *et al.* made a generalizing discriminant analysis by using the generalized singular value decomposition [10]. Jing *et al.* used semi-supervised singular value decomposition for multi-label classification [11]. Because the SVD method is one of the basic theories used in this paper, we first briefly introduce it. The F is defined as the information matrix, which is constructed by the results of multi- comprehensive evaluation methods. For information matrix F mapping vectors in n-dimensional space to p-dimensional space, real matrix F can be decomposed into:

$$F = UWV^T \tag{1}$$

where U is orthogonal matrices of m order and V is orthogonal matrices of n order, and the W is defined as:

$$W = [\begin{matrix} H & 0 \\ 0 & 0 \end{matrix}] = U^T F V \quad (2)$$

where H is the singular value of F, and the H is a diagonal matrix, which is arranged in descending order. The common of the F is extracted and the noise information is stripped, which is expected that the adjustment process from F to Z can minimize the errors between the evaluation conclusions and improve the consistency between the conclusions. At the same time, it is expected to retain F as much as possible to avoid the deviation of Z from F. The singular value optimization needs to take into account both the two indexes.

The credibility index, the t_k, reflects the information quantity of F contained in Z. It refers to the degree of closeness between Z and F, which is defined as:

$$t_k = \sum_{i=1}^{k} \frac{H_i}{\sum_{i=1}^{p} H_i} \quad (3)$$

where p is the number of H, and the k is the reserved number of H.

The consistency index, the T_k, reflects the approximation degree between Z and F, which is defined as:

$$T_k = \frac{||F|| - ||F_k||}{||F|| - ||F_1||} \quad (4)$$

where ||.|| is 2-norm.

In order to meet the requirements of t_k and T_k, a composite index, KX_k, is constructed, which is defined as:

$$KX_k = a_1(b_1 T_k + b_2 t_k) + a_2(b_1 T_k \times b_2 t_k) \quad (5)$$

where the $b_1 T_k + b_2 t_k$ is a linear combination part in the condition $b_1 + b_2 = 1$, which shows that t_k and T_k can complement each other functionally; The $T_k t_k$ is a non-linear part, which emphasizes the equilibrium of t_k and T_k; the $a_1^2 + a_2^2 = 1$ considers the integration of equilibrium and complementarity.

The values of b_1 and b_2 are set according to the relative importance of t_k and T_k. And the values of a_1 and a_2 are selected according to the maximum degree of dispersion, which is defined as:

$$I = \sum_{i=1}^{p} [KX_k - \frac{1}{p} \sum_{i=1}^{p} KX_k]^2 \quad (6)$$

In the condition $a_1^2 + a_2^2 = 1$, the optimal k value is selected according to (6), and the k-order singular value in H is reserved where the W^n is obtained. We can get the optimization matrix Z based on U, W^n, and V.

$$Z = U W^n V^T \quad (7)$$

B. THE SINGULAR ENTROPY

As an improved form of information entropy, the larger the singular entropy (SE) is, the more complex and more vibrant the information contained in the matrix is. The changing trend of information singular entropy can be used to judge the quality of the information matrix. He *et al.* used the singular entropy for fault detection and classification in the extremely high-voltage transmission [12]. Zhang *et al.* presented a new technique called morphology singular entropy (MSE), based on which a phase selector for transmission lines is developed [13]. Samui and Samantaray presented wavelet singular entropy (WSE)-based islanding detection in distributed generation (DG) interfaced to the microgrid [14].

The singular value H_i is used to describe the quantitative comparison of features in the F, so H can react objectively to the F. The SE of F is defined as:

$$E_k = \sum_{i=1}^{k} \Delta E_i \quad (8)$$

where k is the order of SE and ΔE_i is the increment of SE in order i, which is defined as :

$$\Delta E_i = (H_i \sum_{j=1}^{n} H_k) log(H_i \sum_{j=1}^{n} H_k) \quad (9)$$

C. THE KENDALL CORRELATION COEFFICIENT

The KENDALL coefficient, as a measure of correlation degree, has been applied in many fields. Buzaglo and Etzion considered codes in the set of all permutations on n elements, S_n, using the Kendall -metric [15]. Jiao and Vert shown that the widely used Kendall tau correlation coefficient, and the related Mallows kernel are positive definite kernels for permutations [16]. Snake-in-the-box codes under Kendall's tau -metric were studied in the rank modulation scheme for flash memories [17]. Based on the above studies, we choose the KENDALL coefficient to measure the correlation between Z and F, the G, which is defined as:

$$G = \frac{12 \sum_{i=1}^{n} (\sum_{j=1}^{m} r_{ij} - \frac{1}{n} \sum_{j=1}^{m} r_{ij})}{m^2(n^3 - n) - (m \sum_{i=1}^{m} \sum_{i=1}^{m_i} (n_{ij}^3 - n_{ij}))/12} \quad (10)$$

where the r_{ij} is the value of j_{th} evolution method on the i_{th} object, and the m_i is the number of repetitive ordinal values in the evaluation results of the i_{th} comprehensive evaluation method. The n_{ij} is the j_{th} repetitive value in the evaluation conclutions of the i_{th} evaluation method.

The (10) considers that the optimized conclusion Z is significantly consistent with the F and can reflect the information contained in the F, which is defined as:

$$X_n^2 \geq X_\alpha^2 \quad (11)$$

where X_α^2 is the critical value in the α level, which can check from the KENDALL correlation coefficient significance critical value table. The X_n^2 is the significance of the G, which is defined as:

$$X_n^2 = m(n-1)G \quad (12)$$

D. THE TFN TYPE UNCERTAIN MULTIPLE ATTRIBUTE EVALUATION METHOD BASED ON RSR

Aiming at uncertain multi-attribute evaluation(UMAE) problems with uncertain information, such as objectivity, ambiguity, complexity of things and environment, limitation of human knowledge structure, level, subjectivity and preference of thinking judgement, people often use the uncertain form of triangular fuzzy number to describe the attribute evaluation value of finite schemes and use it to compare schemes, which is defined as :

$$x_{ij} = [x_{ij}^L, x_{ij}^M, x_{ij}^U] \tag{13}$$

where x_{ij}^L is the lower element of x_{ij}, x_{ij}^U is the upper element of x_{ij} and x_{ij}^M is the special element of x_{ij}, the x_{ij} can fully reflect the UMAE problems from many perspectives. And the x_{ij}^M is the most probabilistic value and the probability of getting the value from the x_{ij}^U or the x_{ij}^L decreases.

1) NORMALIZATION

There are different dimensions in the index system, and there is incommensurability among dimensions. To eliminate this incommensurability, the r_{ij} is coveted from x_{ij}, which is defined as:

$$r_{ij} = [\frac{x_{ij}^L}{\sum_{i=1}^n x_{ij}^L}, \frac{x_{ij}^M}{\sum_{i=1}^n x_{ij}^M}, \frac{x_{ij}^U}{\sum_{i=1}^n x_{ij}^U}] \tag{14}$$

$$rij = [\frac{\frac{1}{x_{ij}^L}}{\frac{1}{\sum_{i=1}^n x_{ij}^L}}, \frac{\frac{1}{x_{ij}^M}}{\frac{1}{\sum_{i=1}^n x_{ij}^M}}, \frac{\frac{1}{x_{ij}^U}}{\frac{1}{\sum_{i=1}^n x_{ij}^U}}] \tag{15}$$

where (14) is for fundamentality-oriented dimension indexes, while (15) is process-oriented dimension indexes. And the x_{ij} is the interval of the j_{th} dimension of the i_{th} object and n is the number of evaluated objects.

2) WEIGHT OF DIMENSIONS

Referring to the maximum weighting algorithm based on game theory, the smaller the total relative similarity of the evaluation values of all the evaluated objects in the same dimension is, the larger the measurement value of the dimension weight is. The weighted vector of first level dimension w, which reflects the relative similarity between the dimension attribute values of each evaluated object is defined as

$$w_j = \frac{\sum_{k=1}^n \sum_{i=1}^{i<k} S(r_{ij}, r_{kj})}{\sum_{j=1}^l \sum_{k=1}^n \sum_{i=1}^{i<k} S(r_{ij}, r_{kj})} \tag{16}$$

where the S_j is the similarity of different intervals between the same dimension, which is defined as

$$S(r_{ij}, r_{kj}) = \frac{\sum_{i=1}^l r_{ij} r_{kj}^T}{max(r_{ij} r_{ij}^T, r_{kj} r_{kj}^T)} \tag{17}$$

where $S(r_{ij}, r_{kj})$ represents the similarity of i_{th} and the k_{th} evaluated object in the j_{th} dimension interval, and l is the number of dimension.

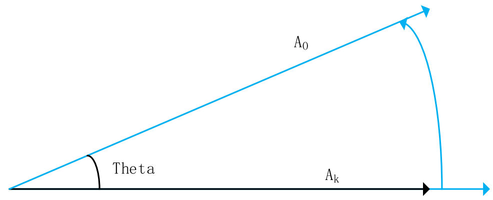

FIGURE 1. The principle of consin.

By using the w and the r, the weighted evaluation matrix X can be obtained, which is defined as

$$X_{ij} = r_{ij} w_j \tag{18}$$

where X_{ij} is the j_{th} dimension scoring interval of i_{th} evaluated object.

3) RELATIVE SIMILARITY RELATION

And the assessment vector U_i can be constructed based on X, which is defined as:

$$U_i = (X_{i1}, X_{i2}, \ldots, X_{il}) \tag{19}$$

The positive ideal interval is constructed by positive ideal evaluation objects, which is defined as:

$$U^+ = (X_1^+, X_2^+, \ldots, X_l^+) \tag{20}$$

where X_j^+ is the j_{th} dimension positive ideal evaluation value, which is the maximum value in the j_{th} dimension.

The negative ideal interval is constructed by negative ideal evaluation objects, which is defined as:

$$U^- = (X_1^-, X_2^-, \ldots, X_l^-) \tag{21}$$

where X_j^- is the j_{th} dimension negative ideal evaluation value, which is the minimum value in the j_{th} dimension.

$RS(U_i)$ is the overall relative similarity of the relative similarity between the evaluated object and the ideal interval, which is defined as:

$$RS(U_i) = \frac{S(U_i, U^+)}{S(U_i, U^+) + S(U_i, U^-)} \tag{22}$$

where $S(Ui, U^+)$ is the relative similarity of i_{th} evaluated object between itself and positive ideal interval, and $S(Ui, U_-)$ is the relative similarity of i_{th} evaluated object between itself and negative ideal interval. The greater $S(Ui, U^+)$ and the smaller $S(Ui, U^-)$, the $RS(U_i)$ is better.

E. COSINE VALUE

Salton proposed the vector space model [18], which was initially mainly used in information retrieval and other fields. By calculating the cosine value of the angle between the user's query information vector and the document vector being retrieved, the similarity between the query information and the document is quantitatively expressed.The principle is shown in Fig. 1.

Where the I_n is the actual value of the n_{th} index, which is defined as

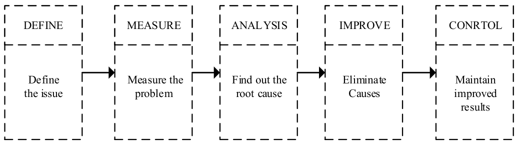

FIGURE 2. The six sigma management strategy- DMAIC mode.

According to the relativity of cosine ranking, the optimal target vector of the evaluated object is introduced, which is defined as

$$O = (O_1, O_2, \ldots, O_n) \tag{23}$$

where the O_n is the maximum value of the n_{th} index.

We can transfer O_n as a n-dimensional coordi-nate system A_O, which is defined as

$$A_O = (a_1, a_2, \ldots, a_n) \tag{24}$$

Similarly, The I can be transferred as a n-dimensional coordinate system A_k, which is defined as

$$A_k = (a_{k1}, a_{k2}, \ldots, a_{kn}) \tag{25}$$

A certain point in space is chosen as the common standpoint, and the index value corresponding to the A_o is taken as the end point to form the directed line segment o_{ak}. Moreover, the index value corresponding to the evaluated object A_k is taken as the end point to form the directed line segment o_{akj}. The cosine value of index can be defined as

$$cos\theta_{in} = \frac{a_{ki}}{a_i} \tag{26}$$

F. THE SIX SIGMA MANAGEMENT STRATEGY

The Six Sigma management strategy optimizes the management process and improves management efficiency, which has been applied in various fields. With Tefen's help, Intersil found technical bottlenecks in the photo area and quickly formed a team to develop a comprehensive capability and cycle improvement roadmap [19]. The application of the Six Sigma method based on DMAIC in improving the fracture resistance of small and medium TFT liquid crystal displays in Literature [20]. Giuseppe Parise explores an innovative design strategy for building power systems by introducing standards based on the ''installation method'' and ''operation method'' and applying the PDCA cycle [21].

The DMAIC method is a process improvement method consisting of five stages: Define, Measure, Analysis, Improve, and Control. The specific process is shown in Fig.2. The definition needs to find things to be improved: measuring data; evaluating the current level; analyzing the causes of problems; taking measures to improve; controlling the effect of improvement.

PDCA divides the improvement into four stages, namely ''Plan - Do - Check - Action''. Four stages of the continuous cycle will improve the management level, the ''control stage'' in DMAIC will be used in PDCA mode, forming closed-loop management, improve the management level, as shown in Fig.3.

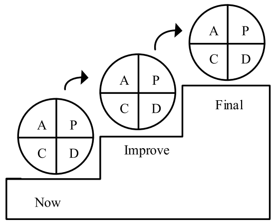

FIGURE 3. The six sigma management strategy- PDCA mode.

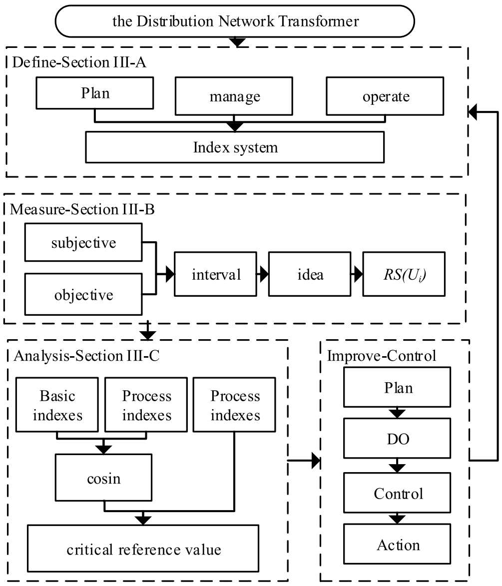

FIGURE 4. The idea of the management about DNTO.

III. THE MANAGEMENT OF DNTO

The Power grid companies can integrate comprehensive evaluation with DMAIC and PDCA management strategy at all stages in the management of DNTO. According to the DMAIC model, the process of the DNTO management in power grid companies is optimized, and the necessary guidance and supervision are given to the power grid companiey by the PDCA model, which is formed to achieve the continuous improvement of the closed-loop management and whose idea is shown in Fig.4.

Define: Establish a relevant index system which can comprehensively and impartially measure the DNTO.

Measure: Evaluate DNTO by using index syestem data.

Analysis: Find out the disparity causes of the DNTO, that is, to distinguish the disparity from the critical reference value and benchmarking.

Improve: Plan some approaches to optimize the DNTO and make the approach.

Control: Control improvement is to observe the approach effect by comparing the data in recent years, to form a check feedback mechanism and to take corresponding actions, which forms a closed-loop management of the DNTO.

A. THE DATA INDEX SYSTEM OF THE DNTO (D)

The effectiveness of the DNTO management depends largely on the selected index system. The rapid development of smart

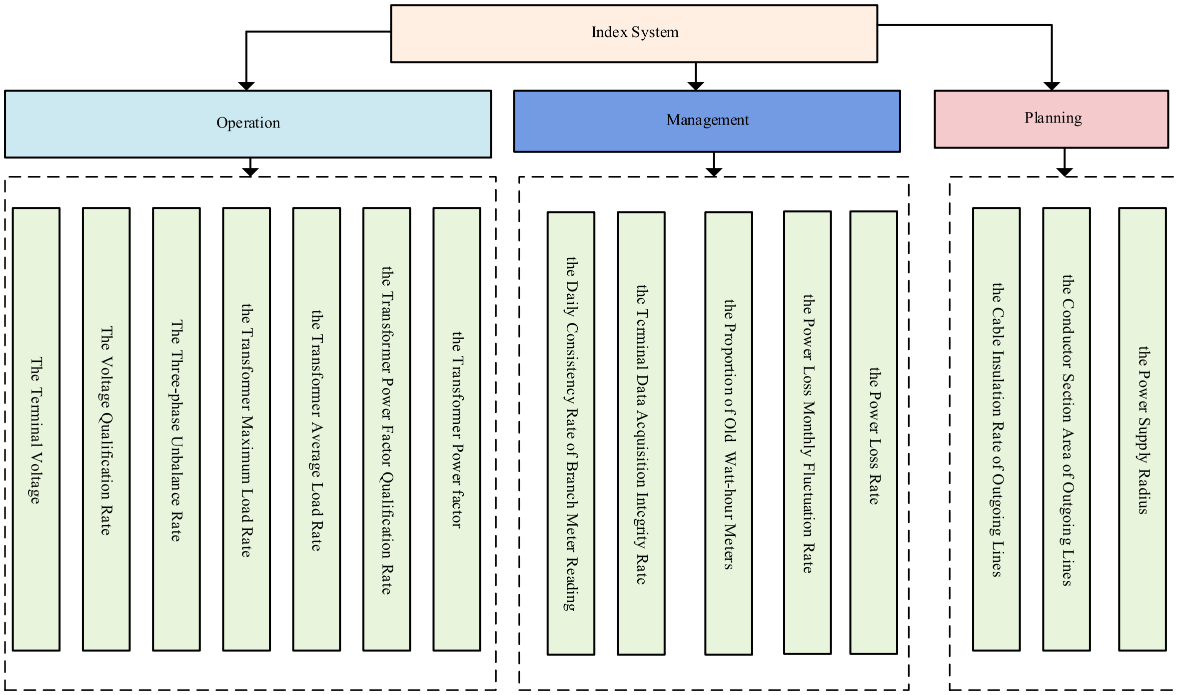

FIGURE 5. The index system of DNTO.

grid and communication technology, as well as the standardization of power grid files, terminal data and file data together constitute the big data of DNTO.

From three dimensions covering the whole process of the DNTO, the evaluation system is constructed, which includes planning characteristics, management characteristics and operation characteristics. Polling distribution network specialists, director of the planning department and other distribution network experts, according to the six principles of index screening which is shown in TABLE 3, build evaluation indexes in three dimensions. The index system of the DNTO is shown in Fig. 5.

1) The planning characteristics mainly refers to the line parameters connected by distribution network transformers, including the power supply radius (1), conductor section area (2) of outgoing lines and cable insulation rate of outgoing lines (3).

2) The management characteristics reflects the management of the distribution network transformers, including the power loss rate (4), the power loss monthly fluctuation rate (5), the proportion of old watt-hour meters (6), the terminal data acquisition integrity rate (7), the daily consistency rate of branch meter reading (8).

3) The operation characteristics refers to the operation of the distribution network transformers, including the transformer power factor (9), the feeder power factor qualification rate (10), the transformer average load rate (11), the transformer maximum load rate (12), the three-phase unbalance rate (13), the voltage qualification rate (14), the terminal voltage (15).

B. THE MANAGEMENT ASSESSMENT OF DNTO (M)

In order to effectively use the data index system to measure the DNTO, the concept of "group wisdom" is introduced. The group wisdom under the management of the DNTO is defined as: "Individuals transform their knowledge of management of the DNTO into shared wisdom through mutual cooperation or other mechanisms".

1) THE COMPREHENSIVE INTERVAL

Many independent algorithms can reflect many aspects of the DNTO. In this paper, "individual wisdom" such as the fuzzy analytic hierarchy process [22]–[24] (f_1), the variable weight theory [25], [26] (f_2), the entropy weight method [27], [28] (f_3), the coefficient of variation method [29] (f_4) are used to calculate the DNTO index system, and the standpoint of them are different. Such as the analytic hierarchy process emphasizes expert experience, the variable weight theory emphasizes the rational distribution of indicators, and the entropy and coefficient of variation analyze the characteristics of indexes data from different perspectives. The conclusion matrix F is

$$F = [f_1, f_2, f_3, f_4] \tag{27}$$

The conclusion vector F can cover many aspects of the current evaluation. Therefore, the comprehensive interval of the dimension constructed by them can reflect the comprehensive characteristics of the DNTO in an overall way, avoiding the one-sidedness of a single algorithm, which is defined as

$$x = [x^L, x^M, x^U] = [min(F), SVD(F), max(F)] \tag{28}$$

TABLE 1. The relation of indexes.

index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	+														
2		+													
3			+												
4	+	+	+	+		+	+	+	+	+	+	+	+	+	+
5	+	+	+		+	+	+	+	+	+	+	+	+	+	+
6						+									
7							+								
8								+							
9	+	+	+			+	+	+	+						
10	+	+	+			+	+	+	+	+					
11											+				
12												+			
13	+		+										+		
14	+	+	+						+	+			+	+	
15	+	+	+						+	+			+		+

where x^L is the lowest value, x^U is the most upper value, and the x^M is the optimized value based on SVD Optimization, whose process as follow:

Firstly, the W is obtained based on F according to equation(2), by which we can get the value of the H.

Secondly, in order to avoid the repetition of the selected calculation method, the SE is used to check the amount of information which is can be got according (9-10). If the SE increases monotonously, it is an effective matrix. Otherwise, it is invalid and the duplicate algorithms need to be eliminated.

Thirdly, according to (3), the t_k can be calculated, and the T_k can be obtained based (4). Considering the equilibrium relationship between T_k and t_k, let $b_1 = b_2 = 0.5$, and use software MATLAB 2018b to solve the value of a_1 and a_2 according to the planning model (6).

In addition, according to (7), the KX value is calculated to measure the approximation effect of the matrix. Retaining H_k, set the remaining singular values to 0, and solve the optimization result Z according to (8) based on the KX.

Finally, the G is obtained by (11) based on the Z and the F, and X_n^2 is calculated by (12). According to the X^2 distribution table of $df = N-1$, the critical value X^2 is found. If the (13) is satisfied, according to the G value and saliency check result, the Z is highly consistent with the F, so the Z can reflect the F.

2) THE INTERVAL PROCESS

Firstly, to eliminate the incommensurability of different dimensions, for planning feature comprehensive interval x, which can be transferred to r based (15). For operation dimension and management dimension comprehensive interval value x, which can be transferred to r based (16).

Secondly, the S of dimensions is obtained by (18), and the w is obtained by (17). In addition, the X after weighting is obtained by (19).

Finally, construct the U^+ and U^- according to the definition of positive and negative ideal transformer, and calculate $RS(U_i)$ of each evaluated transfomers by (18), (22).

In this paper, an example is taken for the rural distribution network transformers, but $RS(U_i)$ is not clear and intuitive enough. Therefore, the idea rural distribution network transformer is introduced and its percentage is taken into account the current situation of the operation status of all distribution transformers.

C. ANALYSIS THE DEFECT OF THE DNTO (A)

For no-related indexes, the analysis of the DNTO is that benchmarking makes clear the gap of indexes and realizes the refinement of DNTO management. However, for indexes which have related indexes, benchmarking analysis can not scientifically evaluate the gap of the indexes considering the relation of indexes and human factor. Therefore, this paper proposes a method of the CRE of the indexes to explore the deep-seated relationship between indexes.

In order to quantify the influence of relation about related indexes, the cosine theorem is introduced into the above index system. $OA(oa_{k1}, \ldots, oa_{km})$, is obtained, where the ralated indexes are shown in TABLE 1, where '+' means that there is a relationship between the two indexes. And the angle between the index oa_{ij} and the index OA is theta. The cosine value of the angle θ_{ij} is obtained by using the space vector model, which is defined as

$$cos\theta_{ij} = \frac{oa_{ij}}{(OAOA^T)^{\frac{1}{n}}} \tag{29}$$

where n is the number of related index about j_{th} index, and m is the number of index which have related indexes.

Traditionally, the DNTO need to find the insufficiency of their own index data from their own historical data. However, due to the characteristics of the DNTO, the proportion of electricity consumption is close to the same, so we can use the index data with relation of all transformers to find out the defect of the current operation.

Considering the uneven quality of the staff who manage the DNTO, θ_{ij} is selected to calculate. And the oa_{ijop} of index considering its realted index and human factor, where the θ_{ij} is sought by the average of the whole network, in order to find out the weak link of the DNTO, which is defined as

$$oa_{ijop} = ave(cos\theta_{i1}, \ldots, cos\theta_{j1}) * (OAOA^T)^{\frac{1}{n}} - oa_{ij} \quad (30)$$

The oa_{ijop} can be used to correct the shortcomings of the traditional index benchmarking results biased towards the objects with better basic indexes.

D. THE CLOSE-LOOP MANAGEMENT(IC)

Effectively utilizing the difference of index data is also an important problem in management. PDCA is a main implementation method of Six Sigma design site project, which aims at the management problems caused by the insufficiency of site management.

Plan:Analyse the various influencing factors of the problem, find out the main causes of the problem, and formulate specific measures and methods to achieve the goal.

Do:Implement the measures to achieve the goal of improvement. Implementing measures: Implementing measures according to plan, confirming the effect of implementation immediately after implementation, and explaining the completion of implementation measures.

Control:According to the requirements of the implementation plan process, check the implementation effect and find out the experience and problems in the implementation process in time. Assessment of effectiveness: confirm that all measures have been implemented, compare the results before and after the work, confirm the results achieved, and confirm the benefits of the measures.

Action:In view of the successful measures and achievements, standards and systems should be formulated (the lessons of failure can also be incorporated into the corresponding standards and systems), and the results should be solidified and popularized. Summarize the experience, analyze the unsolved problems of this cycle, and enter the next cycle.

IV. CASE STUDY

In this paper, the data of 194 rural distribution network transformers in a certain area in 2018 are taken as an example, and the above-mentioned evaluation process is applied to evaluate them.

A. THE DATA COLLECTION

According to the index system, there are deviations in the understanding of the index because of the uneven level of distribution network managers. The transformer managers, such as the director of the planning department and the filler, are polled by means of "check-check-fill-in form" to ensure the quality of index data and the accuracy of distribution transformer operation.

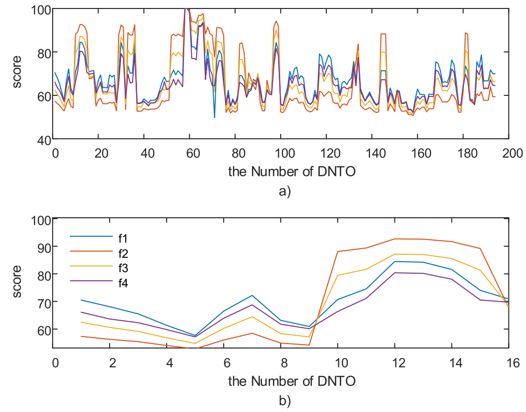

FIGURE 6. The F of DNTO.

B. THE MANAGEMENT ASSESSMENT OF DNTO

The analytic hierarchy process, the entropy weight method, the variable weight theory, coefficient of variation method, and the ideal approximation point are used to evaluate the operation of 194 transformers in the rural distribution network.

Fig. 6 (a) shows that different evaluation methods will get different evaluation conclusions for the data, and because the standpoint of a single algorithm is different, the conclusions will be completely different. Fig. 6 (b) shows that the scores of 7_{th} transformer and 10_{th} transformer calculated by using punitive weight in planning characteristics are 68.76 and 66.34 respectively, 58.46 and 88.07 respectively by using entropy weight method, and 72.19 and 70.68 respectively by using analytic hierarchy process.

The results show that the 7_{th} transformer should have a uniform distribution of its index scores, but not much different from other evaluation stations in the same index. Compared with other indexes of distribution network transformer, the difference of 10_{th} transformer is relatively apparent. However, using a single evaluation algorithm will result in bias in the evaluation of distribution transformer operation.

1) SINGULAR VALUE OPTIMIZATION

In Fig. 7 (a), (b) and (c) we can see that the E of dimension calculated by the (8) (9) increases monotonously with the order of the matrix, which indicates that the comprehensive evaluation methods selected by the F are relatively independent and indicates that the F can fully reflect the DNTO.

As shown in Fig. 7 (d), (e), and (f), it shows that when $k = 1$, the approximation effect of the F of each dimensions are the best. Retain H_1 of each dimensions, set the remaining singular values to 0, and solve the optimization result Z of each dimensions according to (7). According to (10), the G of each dimensions between Z and F is obtained. The (12) can calculate X_n^2, which are shown in TABLE 2.

According to the X^2 distribution table of $D_F = N - 1$, the critical value $X_a^2 = 248.485$ can be found at the $a^2 = 0.05$. According to G value and saliency check result, the Z is highly consistent with the F, so the optimized evaluation value can reflect the F.

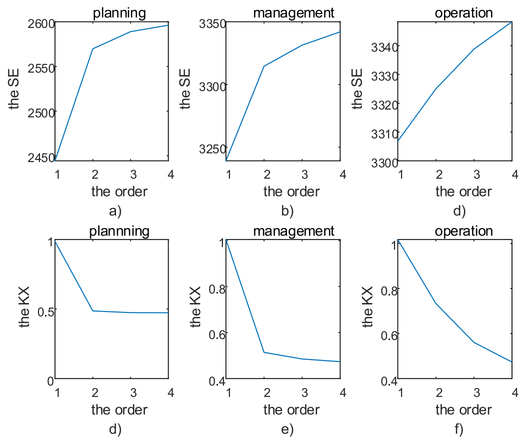

FIGURE 7. The KX and SE of the dimension.

TABLE 2. The result of Kendall.

dimension	G	X_n^2	S	w
planning	0.961	927.221	154.468	0.323
management	0.924	892.193	160.373	0.336
operation	0.985	950.607	162.128	0.339

2) THE x

According to the (2), the x of 7th transformer is [72.19, 65.97, 58.46]. The S of utilization (4) with positive ideal transformer is 0.6208, and with negative ideal transformer is 0.7178. The x of 10_{th} transformer is [88.07, 76.15, 66.34]. The S between the transformer and the positive ideal transformer is 0.6674 by (4), while the similarity between the transformer and the negative ideal transformer is 0.6901. The results show that in the planning dimension, the distance between 10_{th} distribution transformer and positive ideal transformer is closer and that of the negative ideal transformer is farther, so 10_{th} transformer is better than 7_{th} transformer. Converting 7_{th} transformer and 10_{th} transformer into the percentage system is 66.84 and 70.82 respectively. Within the x of the calculation conclusions of the four evaluation methods, the x is flexibly combined with the characteristics of the four evaluation algorithms, in the subjective weighting and data characteristics.

In summary, due to different standpoint and different data, there may be great deviation in the evaluation results due to different methods, and x covers a variety of methods, which can be used to measure the DNTO more comprehensively.

3) RESULT

According to (6), the similarity S between different transformers in the same dimension is obtained, and according to (5), the weighted vector reflecting the similarity between characteristic attribute values of each dimension is shown in TABLE 2. The attribute weight vector and the normative evaluation matrix is substituted into (5) to create the weighted evaluation matrix.

From Fig. 9, it can be seen that the scoring range of rural distribution transformers in the whole area is [60,90].

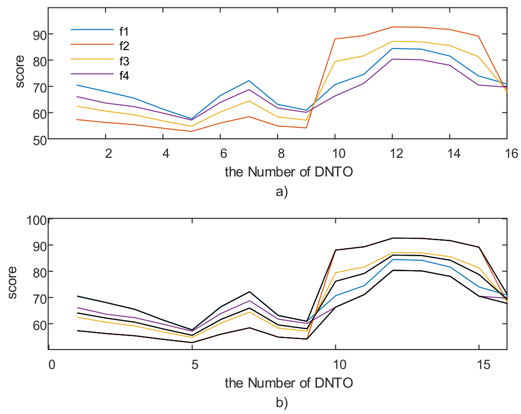

FIGURE 8. The comprehensive interval.

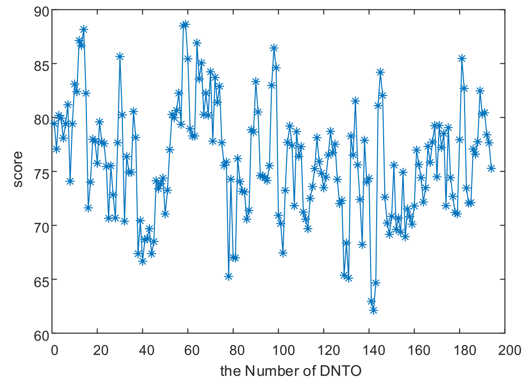

FIGURE 9. The result of evalution.

Among them, the highest score was 5_{th} transformer in the area nearest to the positive ideal and farthest from the negative ideal, with a score of 88.64, while the lowest score was 142_{th} in the area nearest to the negative ideal and farthest from the positive ideal, with a score of 62.12. The average score of transformers in the whole rural distribution network is 75.93, and the partial variance is 5.258. From the data point of view, at present, the DNTO in the rural distribution network in this area is at a low level, which is uneven. Therefore, it is urgent to analyze the DNTO in rural distinct effectively and improve the management of DNTO in the rural rural distinct.

C. ANALYSIS THE DEFECT OF THE DNTO

The 3_{th} transformer (80.19) and 14_{th} transformer (88.17) are analyzed.

1) TRADITIONAL BENCHMARKING ANALYSIS

Fig. 10 (a) shows that the data of 14_{th} transformer in the index 1, 2, 3, 6, 7, 8, is better than that of 3_{th} transformer. Its average score is 91.03, which is higher than 73.42 of the 3_{th} transformer. It has a great advantage, which means that the 14_{th} transformer performs better in the indexes, and does well in installation and popularization of hardware facilities, where the 3_{th} transformer have a huge gap with 14_{th} transformer in index 3 and index 6. In the process index data, the average score of the 3_{th} transformer is 90.15, and

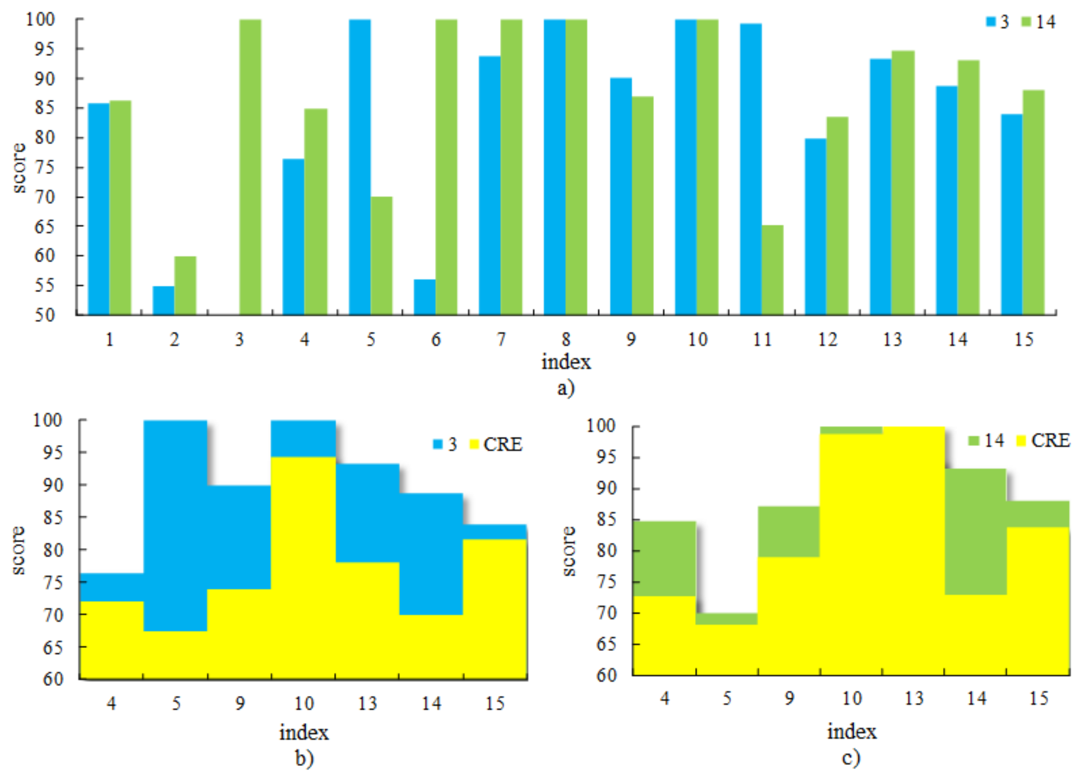

FIGURE 10. The benchmarking of 3_{th} and 14_{th}.

that of 14_{th} transformer is 85.14. Overall, the 3_{th} transformer is slightly better than the 14_{th} transformer. According to the benchmarking results, the performance of 14_{th} transformer in 4, 12, 13, 14 and 15 is better than that of 3_{th} transformer. Therefore, among the five indexes, the 14_{th} transformer should be the learning objectives of the 3_{th} transformer.

2) CRITICAL REFERENCE VALUE ANALYSIS

In order to correct the defect that the process index which have related index is biased towards the object with better basic index, the CRE of the index is introduced to correct the process index benchmarking rusults. According to (30), the cosine angle theta of 194 transformers in the rural distribution network is calculated, and the CRE of each process index of the 3_{th} transformer and the 14_{th} transformer are calculated and analyzed according to (31), which are shown in Fig. 10, respectively.

In Fig. 10 (b), the index value of the 3_{th} transformer is higher than the CRE in the process index, which indicates that the performance of 3_{th} transformer in process indexes is good, higher than the current average level of the rural power network. In Fig. 10 (c), the index 12 of 14_{th}transformer is lower than the critical reference values, while 15 and has just reached the CRE.

According to the comparison between the actual management value and the CRE of 14_{th} transformer in Fig. 10(b), it is concluded that 13 in 14_{th} transformer does not reach the CRE, so index 13 of 14_{th} transformer havs no reference value for learning and need to be rectified immediately to the 3_{th} transformer.

Although the 3_{th} transformer is in a disadvantage in the traditional benchmarking with 14_{th} transformer, 13 has an obvious disadvantage. after introducing the CRE, it is found that the process index of 3_{th} transformer is in good performence and superior to the CRE. According to Fig. 10, the index value of 3_{th} transformer in the process index is higher than its CRE. The no ralated index should be optimized when correcting the result of the benchmarking. 3 and 4 should be optimized to avoid wasting other resources in the optimization of 7, 12, 13, 14 and 15. For 14_{th} transformer, the value of 13 and 11 should be optimized. The difference of 11 is the largest, which indicates that the average load rate of 14_{th} transformer has a big problem.

D. THE CLOSE-LOOP MANAGEMENT

According to the analysis after introducing CRE, the index that the 14_{th} transformer to be revised urgently at present is the average load rate of distribution transformer, the difference of value is 21.59 points, which indicates the current situation of the average load rate of 14_{th} transformer. At present, the average load rate of 14_{th} transformer is 7.66%, and the maximum load rate is only 30.41%. However, the optimization of the load rate of distribution transformer involves not only the index itself but also the power supply radius of distribution transformer and three unbalanced rates of

TABLE 3. The defination of principle.

pricipal	defination
Relevance	Indexes are selected in connection with DNTO
Clear definition	Indexes should have clear and understandable definitions
Consistence	Require that the actual measured value of the index be consistent with its definition
Sensitivity	Indexes are sufficiently sensitive to changes in the state under investigation
Practicability	Requirements for indicators to collect information are true and accurate
Comparability	Requiring that the conclusions drawn by the same fairness index can be compared with each other

distribution transformer feeder. Therefore, according to the principle of PDCA, considering the premise of planning structure, we should reasonably increase the power load, increase the power consumption and improve the utilization rate of the transformer, while avoiding the occurrence of the problems of too long power supply radius and the rising unbalanced rate of distribution transformer feeder.

1) PLAN

(1) The power load of 14_{th} transformer is mainly residential power consumption, supplemented by commercial power consumption. The simultaneous rate of typical days of 14_{th} transformer is analyzed. Monday and Saturday are taken as typical days respectively. According to the formula in reference, the simultaneous rate of transformer is 75.3% and 64.2% respectively. It shows that residents'electricity consumption habits and laws are quite the same, among which the daily load is more concentrated, so the maximum load and the simultaneous rate of the working day should be taken into account to increase the average load rate.

(2) The current user load demand coefficient of 14_{th} transformer is 0.3041, and the service life of the 14_{th} transformer is 16 years. At present, the development of distribution transformer power supply has become mature. Therefore, it is necessary to increase the current peripheral load supply reasonably and improve the current average load rate of the distribution transformer.

2) DO

(1) Manual adjustment of line load. First of all, load adjustment should be carried out to find out the load of the switch in the measurement results. The adjustment scheme is as follows: 1. The Business Department of the all single-phase users in the station area according to the account data calculates the average load through the electricity sales volume and the electricity consumption time, and the formula is average load (kW)=electricity sales volume (kW.h)/time (h).

(2) At present, the power supply radius of 14_{th} transformer is 320 meters, which is far below the requirement of Class E distribution transformer specified by the company. Therefore, on the premise of avoiding "neck jam", the power supply range should be reasonably expanded. By adjusting a load of some residential and commercial transformers in adjacent distribution networks, the number of users increased from 112 to 166, the power supply radius increased by 35 meters, and the working day simultaneous rate was 76.4%. The load demand coefficient of the transformers in this distribution network increased to 0.457, which reached the average level of transformers in urban power distribution networks in this region.

(3) Draw the low-voltage three-phase load distribution map based on the low-voltage wiring diagram, and adjust the three-phase load according to the low-voltage load distribution map. The three-phase load should be adjusted from the last stage to a higher level in order. It should be ensured that the end of the line and the whole distribution network transformer can achieve load balance. It should be noted that the 14_{th} k transformer has a negative load. In the case of overload so that the above method can not be completed even after adjustment, load simultaneous rate needs to be considered, that is, when the single-phase load is added to exceed the capacity, because all loads are not simultaneous, it can be considered that this part of the load can be mixed to reduce the load.

3) CONTROL ACTION

The average load rate of 14_{th} transformer increased from 7.66% to 11.57%, the maximum load rate increased from 30.41% to 45.7%, and the line loss rate decreased from 6.17% to 5.84%. The renovation work has achieved good results, so we should continue to promote the implementation of relevant countermeasures.

V. CONCLUSION

In view of the current situation of DNTO in power grid companies, based on the Six Sigma management strategy and comprehensive evaluation theory, the management of DNTO is optimized. Through simulation analysis, the following conclusions are drawn:

1) According to the idea of big data, the established index system can reflect the distribution transformers'operation comprehensively.

2) Based on group wisdom, the assessment of the DNTO using multi-algorithm fusion is used to measure.

3) Introducing the concept of the CRE of index which have related indexes, further considering the reasonable reference value of index under the action of related index, to better guide the management.

4) Adopt the Six Sigma management strategy, optimize the process of DNTO, ensure the profitability of measures, and realize closed-loop management.

5) In the future, economic factors can be considered to measure the economic benefits of DNTO optimization measures.

APPENDIX
THE DEFINATION OF PRINCIPLE

See Table 3.

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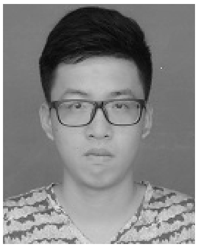

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