Priority Assessment Model of On-line Monitoring Devices Investment for Power Transformers

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Abstract: *Finding an appropriate way to improve the investment comprehensive benefits for on-line monitoring is a new issue for power industry. In this paper, a priority assessment model for transformer on-line monitoring is proposed. The assessment model consists of device level and system level. The device level is divided into property assessment and operation assessment. The details of various assessment methods were described in the following sections, including device property assessment based on fuzzy analytic hierarchy process(FAHP), operation condition assessment method based on condition assessment technology and system level assessment method based on risk benefits index. An actual grid is utilized to validate the model and the numerical results illustrate that: the proposed assessment model can provide an appropriate on-line monitoring investment order for transformers. It also verifies that considering multiple aspects related to the target problem could give a more comprehensive assessment result than just considering just one or two of them. This paper provides a feasible solution to achieve more investment benefits for transformer online monitoring, which can provide on-line monitoring investment references for power industry.*

Key words: *on-line monitoring, priority assessment, FAHP, device property, operation condition, risk benefit.*

1. Introduction

With construction of smart substations and implementation of condition-based maintenance, technology of on-line monitoring for primary equipment have been widely applied in the power sector of China[1-4]. The installation of on-line monitoring devices would affect the failure rate and repair time of the primary equipment. Due to vital role played by transformers in the power system, the installation of on-line monitoring devices makes significant sense for safety, reliability and economy [5-6]. However, there are a significant amount of transformers in the interconnected power grid of China. Taking 200kV transformers as an example, dozens of transformers are installed in a regional city grid. Constrained by limited manpower and financial capacity, the grid corporation normally invests in batches to assess on-line monitoring investment priority based on operation condition and the importance of transformer is worth considering the fact that on-line monitoring devices cannot be installed simultaneously. Therefore, an appropriate way studying and it can improve the investment comprehensive benefits.

To achieve a more comprehensive assessment result, this paper proposes a priority assessment model of on-line monitoring devices for transformer which consists of device level and system level. Specifically, device level covers device property priority assessment and operation condition priority assessment. System level assessment implies that the model assesses risk benefits gained by on-line monitoring devices.

Device property assessment focuses on qualitative factors that influence on-line monitoring devices investment priority, such as cooling mode, service time, record of maintenance, regional environment, etc. In an Analytic Hierarchy Process (AHP), multiple criteria are taken into consideration and organized in a hierarchical structure. Therefore, AHP and its developed methods have been applied in a wide range of problems related to multiple criteria decision-making [7-10] and so is the issue discussed in this paper. Operation condition of individual transformer is another key factor that has an impact on prioritizing investment order. The more severe health condition a transformer is in, the higher priority it has. Condition assessment technology has aroused much concern of researchers. Reference [11] proposed a method of insulation condition assessment of power transformers using fuzzy approach and evidential reasoning. Reference [12] provided a condition assessment method of power transformer according to the association rule and the variable weight. An assessment model of transformer mineral oil condition based on indices of water, acids and gases was proposed in [13]. Reference [14] built a multilayer transformer condition assessment model by integrating matter–element theory and cloud model. Besides, fuzzy support vector machine approach [15-16] is also applied in this field.

On-line monitoring devices can affect the indices of transformer reliability and consequently the risk of power system operation will be influenced. So this paper adopts risk benefits index to evaluate the priority of investment on on-line monitoring devices for transformer in system level. The definition of risk, covering the probability of failure and the corresponding consequences, is applied in many fields of power industry [17]. Reference [18] studied on maintenance and replacement strategy for circuit breakers, transformers, overheard lines and other equipment by evaluation of risk. Reference [19] presented a plan of the network reconfiguration following massive outage based on risk index. On top of that, evaluation of risk was also applied in security assessment of wind-integrated power systems [20], unit restoration [21], and equipment maintenance plan for transmission and transformation [22].

This paper is organized as follows: after introduction, a priority assessment model of on-line monitoring devices for transformer is proposed section 2, including device level and system level and device level is divided into property assessment and operation condition assessment. Then the theory of FAHP and its application in property priority assessment are introduced in section 3. Besides, an operation condition priority assessment method by employing technology of transformer condition assessment presented in previous research [14] is also presented in section 3. In section 4, system level assessment based on risk benefits is described in details. This model is tested with practical cases in section 5 and conclusions are made in the last section.

2. Priority assessment model

In China, the grid corporation takes the responsibility of batch investment on on-line monitoring devices of transformers. It can be uneconomic to equip every transformer with on-line monitoring devices. Therefore, prioritization of installation is helpful for the grid corporation to arrange production activities and enhance the investment benefit. Assessment in this paper aims at evaluating investment priority of on-line monitoring devices for transformers in the identical voltage class. To deduce a more comprehensive assessment result, this paper proposes a priority assessment model consisting of device level and system level. Specifically, device level covers device property assessment and operation condition assessment. System level assessment adopts risk benefits gained by on-line monitoring devices as assessment index. Based on analysis of the three results mentioned above, the order of investment on on-line monitoring devices can be obtained. The model built in this paper is shown in Fig.1.

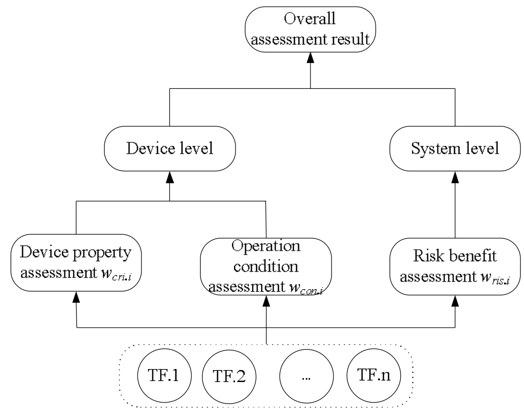

Fig. 1 Priority assessment model for transformer on-line monitoring devices investment

In Fig. 1, the device property index of ith transformer, wcri.i, is gained by assessing device property based on FAHP. wcon.i , which is obtained through the method of condition assessment, reflects the relative operation condition of ith transformer among n transformers. And the index wris.i , which is gained by risk assessment, reflects the value of risk benefits of ith transformer. For each transformer the index of overall priority assessment is given by the weighted sum of three indexes above such as:

$$W_i = \alpha_1 w_{cri \cdot i} + \alpha_2 w_{con \cdot i} + \alpha_3 w_{ris \cdot i} \quad (1)$$

where W_i is the priority assessment index of transformer i and α_1, α_2, α_3 is the corresponding weight of three indexes subject to constraint condition $\alpha_1+\alpha_2+\alpha_3=1$.

3. Priority assessment in device level

A. Device Property Assessment

1) FAHP

In the traditional analytic hierarchy process, the difficulty in pair-wise comparison and subjective judgments of evaluators may make the assessment unreasonable. FAHP employing fuzzy variables to improve the comparison scale produces greater precision and reliability compared with conventional AHP. Procedures of FAHP are shown as follows.

Step 1: Analyze the problem and build a hierarchical structure. Generally the structure is divided into objective level, criteria level and sub-criteria level. The structure of device property assessment level of transformers is illustrated in Fig. 2.

Step 2: Compare the relative importance (priority) of one criterion with another, which typically expressed by pair-wise comparison. Then construct a judgment matrix and determine the respective weight of each criterion. FAHP improves the conventional 1~9 scale with triangular fuzzy number which can be presented as =(p, q, r), where p, r represents the maximum and minimum value and q is the mean value. The improved scale is exemplified in Table I. The constructed fuzzy judgment matrix is $\tilde{A}=(\tilde{a}_{ij})_{n\times n}$, where $\tilde{a}_{ij}$ is the relative importance ratio of criteria i to criteria j and n is the number of criteria.

A reasonable result should reflect composite opinions of field experts such as (2)-(5).

$$a_{ij}=(p_{ij},q_{ij},r_{ij}) \tag{2}$$

$$p_{ij}=(\prod_{k=1}^{m} p_{ijk})^{1/m} \tag{3}$$

$$q_{ij}=(\prod_{k=1}^{m} q_{ijk})^{1/m} \tag{4}$$

$$r_{ij}=(\prod_{k=1}^{m} r_{ijk})^{1/m} \tag{5}$$

where m is the number of experts, k means the kth experts.

TABLE I

FUZZY SCALE FOR FACTOR IMPORTANCE COMPARISON

Fuzzy number	Definition	Description
$\tilde{1}$	Equally important	(1, 1, 2)
$\tilde{2}$	Between $\tilde{1}$ and $\tilde{3}$	(1, 2, 3)
$\tilde{3}$	Moderate importance of one over another	(2, 3, 4)
$\tilde{4}$	Between $\tilde{3}$ and $\tilde{5}$	(3, 4, 5)
$\tilde{5}$	Strong or essential importance of one over another	(4, 5, 6)
$\tilde{6}$	Between $\tilde{5}$ and $\tilde{7}$	(5, 6, 7)
$\tilde{7}$	Very strong or demonstrated importance of one over another	(6, 7, 8)
$\tilde{8}$	Between $\tilde{7}$ and $\tilde{9}$	(7, 8, 9)
$\tilde{9}$	Extreme importance of one over another	(8, 9, 9)
reciprocal	The importance of factor i over factor j is a_{ij}=(p_{ij}, q_{ij}, r_{ij}), then importance of factor j over factor i a_{ji}=(1/r_{ij}, 1/q_{ij}, 1/p_{ij})	

Step 3: Due to the complicacy of objective facts and limits of subjective knowledge, consistency check for the result is necessary. Consistency index (CI) is defined as (6).

$$CI=\frac{\lambda_{\max}-n}{n-1} \tag{6}$$

Where n and $\lambda_{\max}$ are the dimension and maximum eigenvalue of judgment matrix respectively. Research on the calculation of $\lambda_{\max}$ is still a hot issue and it is calculated by an approximate method in the engineering point of view. Extract the mean value of each triangular fuzzy number in the fuzzy judgment matrix and form a new matrix, the maximum eigenvalue of the new matrix is the approximate $\lambda_{\max}$. Average stochastic consistency rate is shown in Table II and consistency ratio is calculated as (7).

$$CR=\frac{CI}{RI} \tag{7}$$

Table II

AVERAGE STOCHASTIC CONSISTENCY RATE

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

When CR<0.1, the consistency of judgment matrix is assumed to be acceptable. Otherwise the element in judgment matrix should be modified approximately and consistency check should be conducted again until CR meets requirement. At last, weight of each criterion is obtained by logarithmic least square method [23].

2) Device property assessment for transformers based on FAHP

a) Hierarchical structure construction

Device property assessment model is illustrated in Fig. 2.

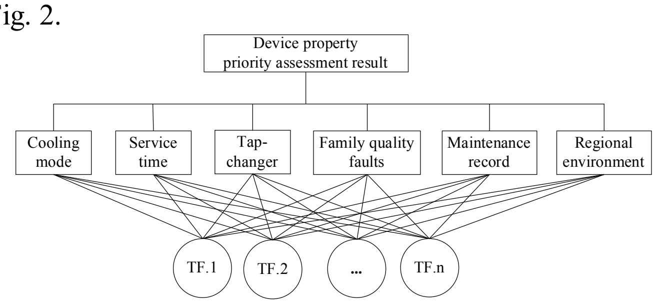

Fig. 2 Hierarchical model for priority assessment for transformer properties

Explanation of Criteria

CRI.1: cooling mode. Usually, on-line monitoring devices are installed on transformers such as oil-immersed transformers in transmission network

(110kV and above). Cooling modes of general oil-immersed transformers are as follows: ONAN, ONAF, OFAF, OFWF, ODAF or ODWF [24]. Cooling mode is related to the voltage level and capacity of transformers, so it is critical to transformer's operation and cooling mode is selected as one of criteria.

CRI.2**:** service time. Under the same circumstances, transformers with longer service time have more aging problems. So service time should be taken into account.

CRI.3**:**Tap-changer. Tap-changer failure is also common issue in transformers and hydrocarbon feature after its action is similar to that of partial discharge [25]. So we should discriminate among transformers without tap-changer, ones with off-circuit tap-changer and ones with on-load tap-changer when assessing on-line monitoring devices priority.

CRI.4**:** Family quality faults. This index refers to the device fault resulted from verified universal factors such as design, material, techniques, etc [26]. It is essential to intensify monitoring of transformers with family quality fault in the recorded fault information.

CRI.5**:** Record of maintenance. The record of maintenance, including time, contents, treatment, conclusion of maintenance which reflects the information of historical operation condition, is one of major references in priority assessment for investment on on-line monitoring devices [27].

CRI.6**:** Regional environments. Adverse environment can influence the operation condition. Furthermore, the cost of maintenance rises accordingly. Regional environment is also taken as a criterion.

Explanation of Sub-criteria

To precisely compare diverse transformers by the same criterion, this paper defines sub-criteria for every criterion. Sub-criteria of the same criterion may differ from each other between different voltage grades. For example, cooling mode changes according to voltage level. Sub-criteria in 220kV network selected in this paper are illustrated in Fig. 3.

Each sub-criterion of the same criterion is assigned a number from 1 to 10. The closer the number is to 10, the more important it is. Then by synthesizing opinions of experts and normalizing the value, weights of sub-criteria can be obtained and illustrated in Table III.

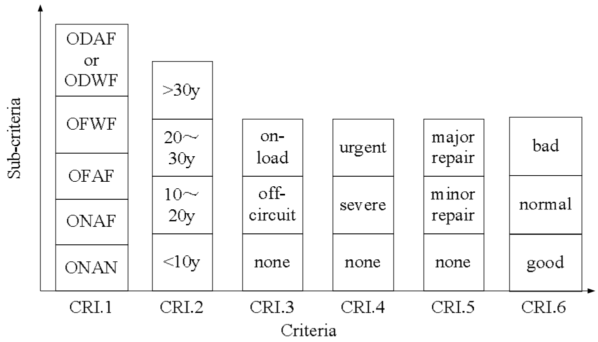

Fig. 3 Sub-criteria definition for 220kV transformers

TABLE III
WEIGHTS OF SUB-CRITERIA

Criteria	Weights of sub-criteria				
CRI.1	ONAN	ONAF	OFAF	OFWF	ODAF/ODWF
	0.0605	0.1256	0.1721	0.2837	0.3581
CRI.2	<10y	10~20y	20~30y	>30y	
	0.1132	0.1745	0.3019	0.4103	
CRI.3	none	Off-circuit	On-load		
	0.0826	0.3058	0.6116		
CRI.4	none	severe	urgent		
	0.0654	0.366	0.5686		
CRI.5	none	Minor repair	Major repair		
	0.1084	0.3083	0.5833		
CRI.6	good	normal	bad		
	0.0833	0.275	0.6417		

b) Judgment matrix construction and weight calculation

Pair-wise comparisons were carried out among the six criteria and fuzzy judgment matrix is built as (8).

$$\tilde{\boldsymbol{A}} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \tilde{a}_{13} & \tilde{a}_{14} & \tilde{a}_{15} & \tilde{a}_{16} \\ \tilde{a}_{21} & \tilde{a}_{22} & \tilde{a}_{23} & \tilde{a}_{24} & \tilde{a}_{25} & \tilde{a}_{26} \\ \tilde{a}_{31} & \tilde{a}_{32} & \tilde{a}_{33} & \tilde{a}_{34} & \tilde{a}_{35} & \tilde{a}_{36} \\ \tilde{a}_{41} & \tilde{a}_{42} & \tilde{a}_{43} & \tilde{a}_{44} & \tilde{a}_{45} & \tilde{a}_{46} \\ \tilde{a}_{51} & \tilde{a}_{52} & \tilde{a}_{53} & \tilde{a}_{54} & \tilde{a}_{55} & \tilde{a}_{56} \\ \tilde{a}_{61} & \tilde{a}_{62} & \tilde{a}_{63} & \tilde{a}_{64} & \tilde{a}_{65} & \tilde{a}_{66} \end{bmatrix} \Rightarrow \begin{bmatrix} \tilde{A}_1 \\ \tilde{A}_2 \\ \tilde{A}_3 \\ \tilde{A}_4 \\ \tilde{A}_5 \\ \tilde{A}_6 \end{bmatrix} \tag{8}$$

$\tilde{A}_i$ is the weight of ith criterion (unnormalized) and calculated by logarithmic least square method as follows.

$$\tilde{A}_i = \sqrt[6]{\sum_{j=1}^{6} \tilde{a}_{ij}} \tag{9}$$

Through a mean operation to fuzzy weight $\tilde{A}_i$ and normalization, final weight of each criterion $\{\boldsymbol{A}_i\}_{i=1}^{6}$, could be obtained.

c) Consistency check

The approximate maximum characteristic root of fuzzy matrix $\tilde{\boldsymbol{A}}$ should be calculated and then the consistency should be checked using (6)-(7).

d) Result of device property assessment

After obtaining weight for each criterion that meets the requirement of consistency check, calculate the result of priority assessment of device property as (10).

$$w_{cri.i} = \frac{\sum_{j=1}^{6} \varepsilon_{ij} \times A_j}{\sum_{i=1}^{6}\sum_{j=1}^{6} \varepsilon_{ij} \times A_j} \quad (10)$$

where $w_{cri.i}$ is the value of device property assessment of ith transformer and ε_{ij} is the value of jth criterion of ith transformer. A_j represents the weight for jth criterion.

B) Operation Condition Assessment

Operation condition is another factor that counts in priority assessment of on-line monitoring investment and acts as the foundation of assessment in system level. This paper conducts operation condition assessment with the multilayer uncertain transformer condition assessment model presented in previous research [14]. The larger the value of condition is, the higher on-line monitoring investment priority the transformer has.

According to the paper [14], calculate probability of diverse operation conditions of transformers, expressed as [g_1, g_2, g_3, g_4]. Expected value of deterioration degrees corresponding to the states are [0.1, 0.35, 0.65, 0.9]. The condition value is calculated as in (11).

$$H = 0.1 \times g_1 + 0.35 \times g_2 + 0.65 \times g_3 + 0.9 \times g_4 \quad (11)$$

Then the result of operation condition priority assessment of the *i*th transformer $w_{con.i}$ is as follows.

$$w_{con.i} = \frac{H_i}{\sum_{i=1}^{n} H_i} \quad (12)$$

where H_i is the condition value of the *i*th transformer and *n* is the number of transformers.

4. Priority assessment in system level

As the failure rate of transformers could be affected by on-line monitoring devices and failure rate of transformers plays critical role in system reliability analysis, risk benefits are defined in this paper based on risk assessment and adopted to evaluate priority assessment in system level.

A) Failure Rate of Transformers

Failure rate is bound up with the states of transformers [18,28]. Relevant research finds that there is an exponential relationship between fault rate and the condition value, which can be expressed in (13) as follows.

$$F(H) = Ae^{BH} + C \quad (13)$$

where $F(H)$ is the failure rate of the transformer with condition value *H*. *A*, *B* and *C* are undetermined constants and the method to calculate their value can be divided into two different cases. If historical data is adequate, we can calculate A, B, C with inversion method [18]. Otherwise by assuming *F* (0), *F* (0.5), *F* (1) as known [28], we could compute the failure of the component.

B) Risk Index Calculation

After collecting data of fault rate of transformers, we can calculate the risk index related to each specific state, expressed as expected energy not supplied (EENS). Procedures of risk assessment are as follows.

1) Build the model of load grade. Referring to analysis in section 4.3., we find that the computing result is the relative comparison of potential maximum risk benefits. So this paper merely focuses on peak load.

2) Obtain system state by enumeration and calculate the probability that the system is in state S with (14) as follows.

$$P(S) = \prod_{i=1}^{n_d} PF_i \prod_{i=1}^{n-n_d} (1 - PF_i) \quad (14)$$

where n_d indicates the number of fault elements in state S and n is the number of components. PF_i is the unavailability of component *i* and can be calculated with (15) as follows.

$$PF_i = F(H_i) \times r_i / 8760 \quad (15)$$

$F(H_i)$ is the fault rate of component *i* with condition of H_i and its measurement unit is times per year. r_i is the average repair time and its measurement unit is hour.

3) Contingency analysis. Regarding to selected system state, employ the following DC optimal power flow model to calculate load curtailment. If the load curtailment is not equal to zero, define it as failure state and record its probability $P(S)$ and load curtailment $CD(S)$. DC optimal power flow model can be expressed as follows.

$$\min \sum_{i \in ND} CD_i \quad (16)$$

$$\boldsymbol{T}(S) = \boldsymbol{A}(S)(\boldsymbol{PG} - \boldsymbol{PD} + \boldsymbol{CD}) \quad (17)$$

$$\sum_{i \in NG} PG_i + \sum_{i \in ND} CD_i = \sum_{i \in ND} PD_i \quad (18)$$

$$PG_i^{\min} \le PG_i \le PG_i^{\max} \qquad i \in NG \quad (19)$$

$$0 \le CD_i \le PD_i \qquad i \in ND \quad (20)$$

$$|T_k(\mathrm{S})| \le T_k^{\max} \qquad k \in L \quad (21)$$

where $\boldsymbol{T}$(S) indicates vector of line active power flow in the state *S* and $\boldsymbol{A}(S)$ is the relation matrix between active power flow and power injection. ***PG*** is the vector of output power of generation and ***PD*** is the vector of load. ***CD*** is the vector of load curtailment. PG_i, PD_i, CD_i and $T_k(S)$ are the elements of ***PG***, ***PD***, ***CD***, ***T***(*S*). PG_i^{min}, PG_i^{max}, and T_k^{max} are the boundary of PG_i, $T_k(S)$. *NG*, *ND* and *L* indicate generation bus set, load bus set and branch circuit set.

4) Calculate EENS (MW.h/a)

Since this paper merely considers the case of peak load, we can calculate EENS with (22) as follows.

$$EENS = \sum_{S\in SF} P(S)\times CD(S)\times D \qquad (22)$$

Where *SF* is the failure state set in the case of peak load. *P*(*S*) is the probability of failure state *S*. *CD*(*S*) is total load curtailment (MW). *D* is computing time and its value in the paper is 8760h.

C) Risk Benefits Assessment Model in System Level

To evaluate the priority of on-line monitoring devices investment for transformers, we define three states as follows: current state (state 0), future state with on-line monitoring devices installation (state 1), and future state without on-line monitoring devices installation (state 2). Assuming condition score of the *i*th transformer in state 0 is H_i, the fault rate is $F(H_i)$ and average repair time is r_i. According to relevant research [5,6], failure rate and repair time in state 1, with online monitoring devices installation, can be reduced 87% and 70% at most compared with that in state 0. Here this paper defines that if the device fault rate calculated with this proportion is lower than F(0), we assume the minimum fault rate in state 1 is F(0) and the result can be modified based on reliable data of on-line monitoring devices from local grid corporation. The paper [6] indicates that fault rate in state 2 can reach 300% of that in state 0 in the most severe situation. But the author fails to provide a reasonable interpretation on the figure. This paper views that the most severe situation implies the transformer is in severe state and the grid corporation must arrange power-off maintenance as soon as possible, namely when the condition score reaches over 0.8. So the failure rate in state 2 is assumed to be *F*(0.8) and average repair time is equal to that in state 0.

When considering the risk benefits from on-line monitoring devices, we need take both $R_{ben,}$, the reduced risk with installation, and R_{tor}, the increased risk without installation, into consideration. So this paper aggregates $R_{ben,}$ and R_{tor} to calculate risk benefits.

$R_{ben,}$ can be computed in (23) as follows.

$$R_{ben.i} = EENS_{i.0} - EENS_{i.1} \qquad (23)$$

R_{tor} can be computed in (24) as follows.

$$R_{tor.i} = EENS_{i.2} - EENS_{i.0} \qquad (24)$$

Risk benefits of the *i*th transformer can be computed in (25) as follows.

$$R_{bt.i} = R_{ben.i} + R_{tor.i} = EENS_{i.2} - EENS_{i.1} \qquad (25)$$

Assessment value of risk benefits of the *i*th transformer in system level is $w_{ris.i}$ and it can be calculated in (26) as follows.

$$w_{ris.i} = \frac{R_{bt\cdot i}}{\sum_{i=1}^{n} R_{bt\cdot i}} \qquad (26)$$

Where $R_{ben.i}$ is the reduction of system risk from the installation in the ith transformer and $R_{tor.i}$ is the augment of system risk because of lack of on-line monitoring devices for the ith transformer. $EENS_{i.0}$, $EENS_{i.1}$, and $EENS_{i.2}$ are the expected energy not supplied in state 0, state 1 and state 2. For contrast, while calculating the risk benefits of the *i*th transformer we assume the remaining transformer parameters are the same to that in state 0.

5. Case study

To validate the model, this paper applies it to a city grid of Jinan in Shandong Province of China. The active load is 3589MW. There are 14 220kV substations, 28 220kV transformers, 115 nodes and 149 branches. Based on this, priority assessment of on-line monitoring devices investment for 6 transformers is elaborated below.

A) Device Property Assessment

Types of the 6 transformers are: SFSZ10-180000/220, SFPSZ9-180000/220, SSZ-180000/220, SFSZ10-180000/220, SFPS-150000/220 and SFPSZ7-150000/220. Number them sequentially as TS.1 – TS.6.

Ten experts' evaluation is synthesized based on (2)-(5) to obtain the fuzzy judgment matrix of 6 criteria in device property assessment, expressed in (27). Calculate the approximate maximum characteristic root of the matrix and we have λ_{max} =6.21. Furthermore, CR is equal to 0.034 which meet the requirement of consistency check. Calculate fuzzy weight with (9) and the result after defuzzification and normalization is shown below in (28).

$$\tilde{A}=\begin{bmatrix} (1,1,2) & (0.35,0.55,0.81) & (0.23,0.31,0.44) & (0.17,0.2,0.25) & (1,1,2) & (2,3,4) \\ (1.23,1.83,2.90) & (1,1,2) & (0.31,0.44,0.81) & (0.19,0.23,0.31) & (1,1.62,2.66) & (2.52,3.27,4.28) \\ (2.26,3.27,4.28) & (1.23,2.26,3.27) & (1,1,2) & (0.27,0.38,0.62) & (1.62,2.16,3.25) & (2.66,3.67,4.68) \\ (4,5,6) & (3.27,4.28,5.28) & (1.62,2.66,3.67) & (1,1,2) & (2.66,3.67,4.68) & (4.28,5.28,6.28) \\ (0.5,1,1) & (0.38,0.62,1) & (0.31,0.46,0.62) & (0.21,0.27,0.38) & (1,1,2) & (2.35,3.37,4.37) \\ (0.25,0.33,0.5) & (0.23,0.31,0.40) & (0.21,0.27,0.38) & (0.16,0.19,0.23) & (0.23,0.29,0.43) & (1,1,2) \end{bmatrix} \quad (27)$$

$$\tilde{A}=\begin{bmatrix} (0.549,0.6839,1.0609) \\ (0.7532,0.9968,1.5969) \\ (1.2161,1.6772,2.5327) \\ (2.4950,3.2144,4.3563) \\ (0.5545,0.7987,1.1279) \\ (0.2762,0.3392,0.4968) \end{bmatrix} \Rightarrow A=\begin{bmatrix} 0.092 \\ 0.134 \\ 0.219 \\ 0.409 \\ 0.101 \\ 0.045 \end{bmatrix} \quad (28)$$

Take TS. 1 for example, based on its model, we can get that it is a three-phase, ONAF, three-winding and on-load tap changer transformer. The transformer has been in service for 14 years and it does not have any family quality fault. The maintenance record shows that it has been through minor repair. The environment can be evaluated by experts regarding to local situation and in this paper it is set as general. According to Fig. 3, scores of criteria are: 0.1256, 0.1745, 0.6116, 0.0654, 0.3083, and 0.275. Similarly, we can obtain other transformers' scores of each criterion shown in Table IV.

TABLE IV
SCORES OF DIFFERENT CRITERION FOR TRANSFORMERS

	CRI.1	CRI.2	CRI.3	CRI.4	CRI.5	CRI.6
TS.1	0.1256	0.1745	0.6116	0.0654	0.3083	0.275
TS.2	0.1721	0.3019	0.6116	0.0654	0.1084	0.275
TS.3	0.0605	0.1132	0.6116	0.0654	0.1084	0.275
TS.4	0.1256	0.1745	0.6116	0.0654	0.1084	0.275
TS.5	0.1721	0.1745	0.3058	0.0654	0.3083	0.275
TS.6	0.1721	0.1745	0.6116	0.0654	0.5833	0.275

With the weight and scores of each criterion, we can get results of device property priority assessment for TS. 1- TS. 6 and it is shown in Table V.

TABLE V
DEVICE PROPERTY ASSESSMENT RESULTS

	TS.1	TS.2	TS.3	TS.4	TS.5	TS.6
$w_{cri.i}$	0.1770	0.1779	0.1516	0.1621	0.1306	0.2008

B) Operation Condition Assessment

According to the multilayer uncertain transformer condition assessment model presented in previous research [14] and formula (11), we can calculate the operation condition priority assessment of each transformer and corresponding results are illustrated in Table VI.

TABLE VI
OPERATION CONDITION ASSESSMENT RESULTS

	TS.1	TS.2	TS.3	TS.4	TS.5	TS.6
H_i	0.45	0.27	0.38	0.48	0.24	0.32
$w_{con.i}$	0.2103	0.1262	0.1776	0.2243	0.1121	0.1495

C) *Assessment in System Level*

Referring to the parameters of fault rate model of transformers and lines in paper [28], exemplified in Fig. 7, we can calculate the fault rate of each component. Due to the huge number of components, it is impossible to obtain state variables of all of them, so the condition score of the components except 6 transformers involved in evaluation, is set to 0.35. Synthesizing the average repair time in the relevant research [6, 18], repair time of transformer and lines are set to 702*h* and 30*h*, respectively. The relevant variables are illustrated in Table VII.

TABLE VII
PARAMETER VALUES FOR SYSTEM COMPONENTS

	Transformer	Line
A	0.01565	0.01976
B	2.2478622	3.4295969
C	-0.008148148	-0.009756098
r(h)	702	30

Calculate the state probability of single element in failure state and the corresponding load curtailment based on N-1 criterion. With (23)-(26), calculate EENS of each element in diverse states and assessment in system level. The result is shown in Table VIII.

TABLE VIII
SYSTEM LEVEL ASSESSMENT RESULTS

	$EENS_1$	$EENS_2$	R_{bt}	w_{ris}
TS.1	1489.6	1875.2	385.5735	0.1755
TS.2	1582.2	1842.5	260.3237	0.1185
TS.3	1525.4	1889.1	363.7507	0.1655
TS.4	1556.9	1748.1	191.2288	0.0870
TS.5	1528.7	2106.9	578.1500	0.2631
TS.6	1549.2	1967.6	418.3479	0.1904

According to formula (1), we synthesize results of device property, operation condition and risk benefits assessment with α_1=0.2, α_2=0.3, α_3=0.5 and obtain the priority of investment on on-line monitoring devices for 6 transformers shown in Table IX. The score of TS.5 is the maximum, which indicates that TS. 5 possessed the highest priority of investment among all 6 transformers. According to Table IX, results of device property assessment and operation condition assessment of TS. 5 both rank 6^{th} but it ranks first in system level assessment. This can demonstrate that the model can give a more comprehensive result with consideration of several factors rather than a unilateral result because of deficiency of factors considered. We should point out that individual decision-makers can give diverse weight assignment based on their different understanding of device level and system level, which can result in inconsistent assessment.

TABLE IX
COMPREHENSIVE ASSESSMENT RESULTS

	w_{cri}	$w_{con.}$	w_{ris}	Scores	Order
TS.1	0.1770	0.2103	0.1755	0.1882	2
TS.2	0.1779	0.1262	0.1185	0.1327	6
TS.3	0.1516	0.1776	0.1655	0.1664	4
TS.4	0.1621	0.2243	0.0870	0.1432	5
TS.5	0.1306	0.1121	0.2631	0.1913	1
TS.6	0.2008	0.1495	0.1904	0.1802	3

6. Conclusion

Determining the investment priority of online monitoring devices for transformers of the same voltage level can help make optimized investment strategy , which is critical to improve the investment profits and system reliability. This paper proposed a priority assessment model which targets problem that draws more and more attention in China. This model, involving device level and system level related, can give an overall assessment result by integrating device property priority assessment, operation condition priority assessment and system priority assessment based on risk benefit. Conclusions can be made as follows.

1) FAHP can give a comprehensive consideration of several relevant device properties that affect investment priority and through synthesizing a number of experts' evaluations result of device property assessment can be obtained.

2) With risk benefits chosen to be evaluation index, we can consider comprehensively about influences on fault rate and repair time under circumstances with or without online monitoring devices installation. Then we can estimate the benefits of on-line monitoring from the system level point of view.

3) Assessment model with thorough consideration on device property, operation condition and risk benefits can avoid unilateral results by neglecting of other relevant aspects and achieve a more comprehensive result.

Integration of theoretical analysis and case study verifies that the model built in this paper can properly prioritize transformers and provide a reference for strategy of on-line monitoring devices investment. The model is practical and can be applied widely to power industry. Meanwhile, the rationality of assessment can be improved by excavating relevant device properties of the problem and enumerating reliability index of transformers with installation of on-line monitoring devices.

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