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Research on the decision of state maintenance for transmission line based on set pair analysis

Overhead transmission lines are important parts of a power system; their operation state directly affects the reliability level of the entire power system. With the in-depth development of state maintenance work for power grids, correctly evaluating the reliability of overhead transmission lines is the key to successful maintenance. A maintenance decision model for transmission lines is established in this study based on set pair analysis to achieve human financial control and low maintenance efficiency. Full consideration is provided to the influence of environmental factors, and a theoretical basis for transmission line maintenance decision is established.

Keywords: *Overhead transmission line, state maintenance, set pair analysis, reliability*

1. Introduction

The overhead transmission line is the main channel of electric power transmission and the bridge between the power supply and demand sides. Its operation and maintenance are directly related to the safety and smooth operation of the power grid and to whether power energy can be economically or reliably sentor not. Therefore, analyzing the current situation of overhead transmission line operation and maintenance management, identifying problems and deficiencies, developing reasonable measures, and improving the operation maintenance level of transmission lines are important in ensuring the safe operation of a power grid; they also ensure that power is sent reliably and reduce the operation cost of the power system [1-2].

In many developed European and American countries, the development of the electric power system has entered a period of saturation, and power equipment has been gradually aging after many years of operation [3]. A reasonable maintenance strategy must be established to reduce maintenance costs, ensure the safe and stable operation of transmission lines, and gradually improve the competitiveness of enterprises. As a result, power companies in many developed countries have adopted the state maintenance strategyand the maintenance mode (RCM), which is based on reliability, as the specific maintenance method [4]. RCM focuses on the early diagnosis and treatment ofthe abnormal condition of equipment. Equipment condition is the basis for the arrangement of all types of maintenance plans to achieve the highest equipment utilization rate and the lowest maintenance cost. In our country, operation management of transmission lines is mainly based on traditional planned maintenance, and it has been less than 10 years since the concept of state maintenance was introduced. In early 2006, China State Grid Corp. began the construction of related regulation systems of state maintenance. By 2007, China State Grid Corp. completed the preparation of a series of technical standards for state maintenance. By the end of 2009, under the jurisdiction of China State Grid Corp., all the ranges of provincial grid companies were accepted by the state maintenance company's expert group of the China State Grid Corp. Many technical and organizational measures not only remain in the over stage but also need to be further improved because of the late start of China's state maintenance. However, all national network companies have reached a consensus about carrying out state maintenance work; the consensus is that subordinate units could combine with their own conditions and carry out work according to local conditions [5-6].

At present, several problems are encountered in maintenance work because the traditional transmission line management maintenance mode is restricted by human resources and finance condition. Hence, a more scientific maintenance decision scheme must be established. For this reason, a maintenance decision model of transmission lines based on set pair analysis is developed in this study.The model provides a basis for the maintenance decision of transmission lines.

2. Construction of a state maintenance decision ranking model for transmission lines

2.1 Fundamental steps

The basic idea of the analytic hierarchy process (AHP) is to establish a hierarchical structure with independent internal describing the system's function or characteristics [7]. The core issue is scheduling, including the hierarchical structure

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principle, degree theory, and the basic process of the ranking principle hierarchy analysis method. The basic idea of AHP can be roughly divided into six basic steps as follows: Defying the problem, establishing a hierarchical structure, constructing a judgment matrix, hierarchic-single-level sorting, checking consistency, and calculating the weight.

Set pair analysis is a systematic analysis method that combines system science with mathematics; it was proposed by Chinese scholar Zhao Ke Qin. With the advantages of clear concept, simple calculation method, intuitive evaluation and so on, it can deal with the uncertainty problem caused by fuzzy information. With the development and continuous improvement of the theory itself, it has been initially applied in water eutrophication assessment, river basin water resource assessment, flexible power grid planning assessment, power transformer insulation condition assessment, and other fields; it also exhibits broad prospects for development.

The core concept of set pair analysis is the set pair and connection degree, and the core idea is to study the connection and conversion between objective items from three aspects, namely, similar, different, and reverse. A set pair is a whole consisting of two sets having a certain connection with each other. Analyzing the line's quality problem makes the factor index value of the proposed line and the corresponding index values of each line's standard combine two collections. The two collections are combined with one set pair's evaluation criterion, and the sets consisting of a corresponding index are all different.

The basic meaning of the connection degree is that when sets A and B are given, the set that comprises them is expressed as H (A, B). With a specific background the connection degree of the two sets can be established.

$$\mu(A,B) = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j \quad \text{... (1)}$$

In the formula above, N has the total characteristic of every set pair. S, P, and F are common, opposing, and not common, respectively. S/N, F/N, and P/N respectively represent the common degree, difference degree, and opposition degree of two sets under specific problems. For simplicity, a = S/N, b = F/N, and c = P/N; hence, the formula can be rewritten as

$$\mu(A, B) = a + b_i + c_j. \quad \text{... (2)}$$

The formula should satisfy these conditions.

$$a + b + c = 1 \quad \text{... (3)}$$

In formulas (1) and (2), *i* is the difference coefficient and *j* is the opposition coefficient. *i* and *j* have two meanings. The first meaning is that *i* and *j* are the coefficient of the difference degree and opposition degree, respectively. The rule is that in the interval [–1, 1], *i* takes an uncertain value according to different conditions. Generally, *j* takes the value – 1 to show that P/N is contrary to S/N. The second meaning is that the values of *i* and *j* are disregarded. In this case, *i* and *j* only play a marking role; F/N is the difference degree and P/N is the opposition degree, and these two markers have a distinction with the common degree.

Determining whether the relationship between evaluated lines is good or bad involves comparing the connection degree value of evaluated lines' index value set with each evaluation grade standards' index value set. The connection degree value of the evaluated lines has the greatest degree of grade. Assuming that A is the collection combined with every index value of the evaluated line, then correspondingly, B is the collection combined with I, II, and III levels of the standard index value. The quality level of the evaluated line is I. Therefore, the key inset pair analysis is to determine the degree of connection.

The judging standard for similar, different, and reverse aspects is that in the similar aspect, the evaluation index is within the discussed range. In the different aspect, the evaluation index is in the adjacent discussed range. In the reverse aspect, the evaluation index is in the separated discussed range. According to this definition and the judging standard of connection degree, we conclude that

$$\mu(A_1, B_1) = \frac{S_1}{N} + \frac{F_1}{N}i + \frac{P_1}{N}j, \quad \text{... (4)}$$

where S_1, F_1, and P_1 represent the number of indexes in I, II, and III levels, respectively. N is the total number of evaluation indexes.

2.2 Decision process based on set pair analysis

Through the expert investigation method, we established an evaluation index system and set up an evaluation index set; the weight of its corresponding sets is obtained through AHP. The set pair analysis evaluation model includes the following steps.

(1) Through hierarchy analysis, experts set up a judgment matrix to evaluate index importance compared by pairs. Scaling methods 1 to 9 were employed to construct a weighting matrix.

(2) The largest eigen vector was obtained according to the largest eigen value, which is the weight value of each factor. The feature vector was tested for its consistency.

(3) The contact degree of expression was determined. The sample of the quantitative evaluation indexes was regarded as a set of A, and the evaluation standards of the corresponding parameter values are a set of B.

We also combined a collection of A and B into set A. To decide the level of these samples, we compared the connection degree between each evaluation sample index set and each evaluation grade set. For example, to determine the connection degree, we set N as the number of the evaluation items and S as the number of indexes in the range of level I of set A. The corresponding weight is the index number in adjacent level II of sample set A. For this, we have the expression:

$$\mu(A, B_1) = \sum_{t=1}^{s} u_t + \sum_{k=1}^{f} t_k i_k + \sum_{l=1}^{p} v_l j \quad \text{... (5)}$$

Where the weight of sample set A is reflected by the diversity factor between sets A and B.

This step is implemented to determine the diversity factor. With the value in the expression as an example, we assume that a sample index value in the range of level II is the limiting value for levels I and II of this index. We can obtain diversity factor *i* through the fuzzy connection degree of level I standard of the index.

$$\mu(X_k, b_1^k) = a + b_i + c_j \quad \text{... (6)}$$

The value of *i* is a, b, or c separately.

(4) The connection degree number was calculated. With $\mu(A, B_1)$ as an example, we place these values into the expression:

$$\mu(A, B_1) = \sum_{t=1}^{s} u_t + \sum_{k=1}^{f} t_k(a_k + b_k i + c_k j) + \sum_{l=1}^{p} v_1 j. \quad \text{... (7)}$$

In 4.7, we can obtain $i = 0$ and $j = -1$. This method of value assumption shows that we should only pay attention to the critical part of problem evaluation, which is the similarity and difference, based on the analysis of information contained in the evaluation samples. It guarantees the reliability and reasonability of the evaluation result.

Calculation of the connection degree number of each level standard evaluation index set for every line was completed through the steps mentioned above. Then, judgment was made about the level belonging to each sample. Finally, the overall task of ordering decisions according to the transmission line status acquired from poor to good can be implemented.

3. Decision model of transmission line state maintenance based on set pair analysis

3.1 Selection of characteristic parameters

The quality of overhead transmission lines is affected by many factors of control and involves many aspects. How to select the factors that play the major role in ranking decision of transmission line in state maintenance is very important. In the selection of evaluation factors, on the one hand, one must pay more attention to comprehensive analysis to avoid unilateralism of a single factor. On the other hand, one must note that the main factors affecting the transmission line are different because of the difference in climatic condition in different regions. Hence, selection of evaluation factors should be representative and targeted. Filthy parameters, lightning density, amount of bird damage area, line tripping times, and the result of line reliability assessment were selected in this study.

3.2 Constructing the importance matrix of characteristic parameters

Through pair comparison of the fuzzy judgment matrix of the importance of the assessment index set, which includes the containment parameter and lightning density of the line running area, bird damage sector count, important cross line area, times of fault-trip, and estimation of the reliability of lines, we obtain

$$R = \begin{bmatrix} 1 & 2/3 & 1 & 4/3 & 2 & 5/4 \\ 3/2 & 1 & 2/3 & 2 & 3 & 6/5 \\ 1 & 3/2 & 1 & 4/3 & 2 & 4/5 \\ 3/4 & 1/2 & 3/4 & 1 & 3/2 & 3/5 \\ 1/2 & 1/3 & 1/2 & 2/3 & 1 & 2/5 \\ 5/4 & 5/6 & 5/4 & 5/3 & 5/2 & 1 \end{bmatrix}.$$

Then, the correspondingfeature vector can be obtained by calculating $\gamma_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} = 6.059$, which is the importance rate of the model parameter.

The standard established to evaluate the status of the transmission line is shown in Table 1.

The consistence index (CI) of the feature vector is

$$CI = \frac{\gamma_{max} - n}{n-1} = \frac{6.059-6}{6-1} = 0.0118. \quad \text{... (8)}$$

The order of the judgment matrix is 6, and the mean random consistency index RI is 1.24 by look up tables. The random consistency ratio of total ordering indicates that the judgment matrix has a satisfactory consistency parameter, and these vectors can be utilized as the weight vector.

4. Establishment of the maintenance decision model divided into steps

First step: The contamination parameter, thunderbolt density, bird damage-prone areas, important crossing, early tripping frequency, and reliability evaluation of the six index data of lines in the maintenance decision of the transmission line were collected.

Table 1: Standard for evaluating the qualitygrade of the transmission line

Line grade	Contamination parameter	Lightning density	Number of bird damage-prone areas	Important scissors crossing number	Line early stage tripping times	Line reliability evaluation value
I	22-24	3-5	0	0	5	95-97
II	24-27	5-9	1	1	6	92-95
III	27-30	9-13	2	2	7	89-92
IV	30-33	13-16	3	3	8	86-89

TABLE 2: RELATED FAULT CHARACTERISTIC QUANTITY DATA

Tower No.	Code	Fault characteristic quantity	Data results
2#	C36	Failure of the connection device	Pressure pipe bending2.5%
	C30	Locking pin defect	Cotter pin corrosion
4#	C36	Failure of the connection device	Pressure pipe bending 3%
	C12	Wire damage section	Damage depth of left upper sub lead wire in left side 20%
6#	C27	Metal corrosion	79% the mechanical strength of the original value after corrosion
	C32	Vibration hammer defect	vibration hammer loosening
	C4	Bending degree	A surface has a severe bending of a tower material 0.55%
10#	C12	Wire damage section	Damage depth of the upper left superior sub lead of the middle of the medium is 43%
	C1	Corrosion of iron tower and steel tube tower	More bolt corrosion
27#	C30	Locking pin defect	Cotter pin cannotbe inserted
	C3	Component missing and loose	2% of the bolt is missing or loose
71#	C23	Glass insulator	Next phase insulator twenty-third explosion
	C32	Vibration hammer defect	Vibration hammer loosening
	C36	Failure of the connection device	Pressure pipe bending 3%
82#	C32	Vibration hammer defect	vibration hammer loosening
	C36	Failure of the connection device	Pressure pipe bending 3%
	C4	Bending degree	B bent leg members 0.23%
107#	C1	Corrosion of iron tower and steel tube tower	Slight corrosion of bolts
	C3	Component missing and loose	10% of the bolt is missing or loose
115#	C4	Bending degree	C bent leg members 0.20%
	C30	Locking pin defect	Missing nut cotter
	C36	Failure of the connection device	Pressure pipe bending 3%

Second step: Categories were marked as level 1, level 2, and level 3 in the characteristic parameter of line maintenance 6 in turns. The connection of the set of index value in the sample of line maintenance and the connection of the merit value index in line levels 1, 2, 3, and 4 were established on the basis of the same standards.

Third step: The degree of difference between the set of the sample of line maintenance and the evaluation index of merit level k in lines was obtained, and difference coefficient i_k in the connection degree expression was determined.

Fourth step: The set of connection μ(A, B_1), μ(A, B_2), and μ(A, B_3) of the maintenance lines and evaluation grades in the condition were calculated. The connection degree expression between the set of the sample of line maintenance and the set of the merit degree of line levels 1, 2, and 3 was then calculated.

Fifth step: The size of μ(A, B_1), μ(A, B_2), and μ(A, B_3) was compared to determine the degree of merit of the unrepaired line in the condition. The degree of merit in the other lines was then calculated, and a maintenance decision plan was developed on the basis of cracking degree.

5. Example

A 500 kV overhead transmission line (A) was considered. The operation data on January 2010 and the relevant fault characteristics are shown in Table 2.

A 500 kV overhead transmission line (B) was also utilized. The operation data on May 2011 and the relevant fault characteristics are shown in Table 3.

The reliability of the two transmission lines calculated with the fault tree evaluation method is 0.8971 and 0.9554. The environmental data are shown in Table 3, rows 1 and 2. The assessment results of another four transmission lines and other environmental assessment data were utilized to analyze and verify the overhead transmission line maintenance decision-making ranking model. The six lines are numbered S1to S6, and the relevant parameters are shown in Table 4.

The environmental impact on the maintenance decision analysis and the data of six 500kV transmission lines were considered to analyze and verify the overhead transmission line maintenance decision-making ranking model. The characteristic parameters of the index are contamination parameter in the area of the line, thunderbolt density, bird damage-prone areas, important crossing, early tripping frequency, and reliability evaluation of lines. After the experts calculated the characteristic parameter's importance, the result is hydropower.

Among the six factors in the S1 line maintenance plan,

TABLE 3: RELATED FAULT CHARACTERISTIC QUANTITY DATA

Tower No.	Code	Fault characteristic	Data results
21#	C8	Basic protection facilities	Infrastructure damage
	C3	Absence and loosening	2% bolt is missing or loose
26#	C4	Bending degree	D bent leg members 0.21%
	C4	Bending degree	A bent leg members 0.26%
41#	C32	Vibration hammer defect	Vibration hammer damage
	C25	Insulator tilt	Line angle of the insulator string along the line 7.5º
78#	C12	Wire damage section	Lead damage cross section is 7%
	C3	Absence and loosening	12% of the bolt missing or loose
	C4	Bending degree	A bent leg members 0.25%
94#	C29	Degree of wear of the fittings	Mechanical strength of the original 87%
	C23	Glass insulator	Next phase insulator twenty-fourth explosion
	C40	Ground lead off line measurement diameter	Ground lead off line measurement diameter
	C3	Absence and loosening	5% of the bolt is missing or loose
94#	C4	Bending degree	Wood bending is 0.24%
	C23	Glass insulator	On the sixth phase insulator string
109#	C24	Gray dense salt density	Insulator string can withstand salt and ash density at the highest operating voltage 25%
	C41	Bar plate missing	Bar plate missing
119#	C40	Ground lead off line measurement diameter	Design value of the diameter of the grounding wire after the loss of the ground wire is 88%
149#	C8	Basic protection facilities	Base slope damage, mild slope

TABLE 4: BASIC PARAMETERS OF MAINTENANCE RANKING IN SIX UNREPAIRED TRANSMISSION LINES

Line number	Line length/km	Contamination parameter	Thunderbolt density	Bird damage-prone areas	Important crossing	Early tripping frequency	Reliability evaluation of lines
S1	54.3	25	4	1	2	7	95.54
S2	71	30	10	0	1	8	89.71
S3	66	30	13	1	0	5	91.40
S4	65.4	25	7	1	0	5	90.40
S5	57.4	23	7	2	1	6	93.20
S6	73	35	10	3	3	5	87.69

thunderbolt density and reliability evaluation are in level 1 of the corresponding index; their weights are 0.283 and 0.248. The index values of the contamination parameter and bird damage-prone areas are in level 2 of the corresponding index; the weights are 0.159 and 0.159. Important crossing and early tripping frequency are in level 3 of the corresponding index, and the weights are 0.112 and 0.039. The connection of the set of index value in sample S1 of line maintenance and the connection of merit value index in line level 1 on the basis of the same standards can be established as

$$\mu_1(A, B_1) = 0.283 + 0.248 + 0.159i_1 + 0.159i_2 + (0.112 + 0.039)j. \quad ...(9)$$

The level 1 difference coefficient for the contamination parameter of line S1 was calculated as 0.498, 0.001, and 0.501. The difference coefficient for the bird damage-prone areas was calculated as 0.5, 0.5, and 0.

Among the six factors in the S1 line maintenance plan, bird damage-prone areas are in level 1 of the corresponding index; the weight is 0.159. Important crossings are in level 2 of the corresponding index, and the weightis 0.112. The contamination parameter, thunderbolt density, and reliability evaluation of lines are in level 2 of the corresponding index, and the weights are 0.159, 0.283, and 0.248. Early tripping frequency is in level 4. On this basis, the connection of the set of index value in sample S2 of line maintenance and the connection of merit value index in line level 1 can be established as

$$\mu_2(A, B_1) = 0.159 + 0.112i_1 + (0.159 + 0.283 + 0.248)j. \quad ...(10)$$

The level 1 standard coefficient i_1 relative to the contamination parameter of line S_1 is 0.3, 0.15, and 0.45. Therefore, after calculation, we can obtain $\mu_2(A, B_1) = 0.192 + 0.017i + 0.706j$, where $i = 0, j = -1$, and $\mu_2(A, B_1) = -0.514$.

According to the calculation result, the connection between the set of index value in sample S1 of line maintenance and the standard index value in line level 1 on the basis of the same standard is 0.46. The connection between the set of index value in sample S2 of line maintenance and the standard index value in line level 1 on the basis of the same standard is –0.514.

Similarly, the result can be calculated as

μ_1 (A, B_2) = 0.381,

μ_1 (A, B_3) = –0.221;

μ_2 (A, B_2) = 0.071,

μ_2 (A, B_3) = 0.455,

μ_2 (A, B_4) = –0.22.

Therefore, when μ(A, B_1) > μ(A, B_2) > μ(A, B_3), the merit of transmission line S1 is grade 1 and more regular, which is later considered the maintenance decision in the line. For transmission line S2, μ(A, B_3) > μ(A, B_2) > μ(A, B_4) > μ(A, B_1).The merit is grade 3, and hidden faults exist to a certain degree. As a result, the maintenance decision should be considered.

Similarly, the ranking of lines S2, S3, and S4 was calculated.

S2: μ(A, B_3) > μ(A, B_4) > μ(A, B_2) > μ(A, B_1), the ranking is level 3

S3: μ(A, B_3) > μ(A, B_2) > μ(A, B_4) > (A, B_1), the ranking is

TABLE 5: MERIT RANKING OF UNREPAIRED TRANSMISSION LINES IN MAINTENANCE DECISION-MAKING RANKING

Unrepaired lines	Connection degree level	Connection degree value	Merit ranking	Unrepaired lines	Connection degree level	Connection degree value	Merit ranking
S1	Level I standard index value connection degree	0.46	I	S4	Level I standard index value connection degree	–0.03	II
	Level II standard index value connection degree	0.381			Level II standard index value connection degree	0.526	
	Level III standard index value connection degree	–0.221			Level III standard index value connection degree	0.172	
	Level IV standard index value connection degree	–0.384			Level IV standard index value connection degree	–0.751	
S2	Level I standard index value connection degree	–0.514	III	S5	Level I standard index value connection degree	–0.071	II
	Level II standard index value connection degree	0.071			Level II standard index value connection degree	0.603	
	Level III standard index value connection degree	0.455			Level III standard index value connection degree	0.081	
	Level IV standard index value connection degree	–0.22			Level IV standard index value connection degree	–0.762	
S3	Level I standard index value connection degree	–0.459	III	S6	Level I standard index value connection degree	–0.922	IV
	Level II standard index value connection degree	–0.067			Level II standard index value connection degree	–0.519	
	Level III standard index value connection degree	0.229			Level III standard index value connection degree	0.038	
	Level IV standard index value connection degree	–0.032			Level IV standard index value connection degree	0.673	

level 3

S4: $\mu(A, B_2) > \mu(A, B_1) > \mu(A, B_3) > (A, B_4)$, the ranking is level 2

S5: $\mu(A, B_2) > \mu(A, B_3) > (A, B_1) > \mu(A, B_4)$, the ranking is level 2

S6: $\mu(A, B_4) > \mu(A, B_3) > (A, B_2) > \mu(A, B_1)$, the ranking is level 5

The results of the lines are shown in Table 5.

The evaluation results above show that the merit ranking of S1 line maintenance programme is level 1, the merit ranking of S4 and S5 line maintenance programme is level 2, the merit ranking of S2 and S3 line maintenance programme is level 3, and the merit ranking of S6 line maintenance programme is level 4.

Comparison of the line maintenance program between S4 and S5 indicates that the level 2 standard index value of S4 line maintenance is smaller than that of S5 line maintenance. The level 3 standard index value of S4 line maintenance is larger than that of S5 line maintenance. The S4 line is more inclined to the level 3 standard than the S5 line in general. As a result, the level of maintenance decision-making ranking in S4 is higher than that in S5. In the same manner, the level of maintenance decision-making ranking in S2 is higher than that in S3.

In summary, maintenance decision-making ranking in these transmission lines is available by pairwise comparison of the degree of good or bad from transmission lines S1 to S6. As shown in Table 6, a small number indicates a priority maintenance arrangement. Comparison of the final ranking conclusions and reliability evaluation values of the transmission lines shows that the maintenance sequence of the lines is mainly determined by the reliability of the transmission lines. The reason the maintenance sequence of line S2 has a high ranking is that environmental thunderbolt density and contamination grade are severe, a condition that increases the lightning outage and pollution flashover rates. Therefore, line S2 should be considered for priority maintenance. This case shows that transmission line maintenance decision-making ranking considering the environmental variable is more scientific than line maintenance based simply on reliability.

TABLE 6: TRANSMISSION LINE MAINTENANCE DECISION-MAKING RANKING

Unrepaired line number	Merit ranking	Line reliability evaluation	Maintenance sequence
S6	4	87.69	1
S2	3	91.40	2
S3	3	89.71	3
S4	2	90.40	4
S5	2	93.20	5
S1	1	95.54	6

The actual maintenance status indicates that several tower bolts of overhead transmission line S1 need a filling; the operation is normal. Many defects appear in the wires and metal parts of overhead transmission line S2, and the operation is normal after the wires of tower 10 # have been repaired and other wires and metal parts in the towers have been repaired and adjusted.

Conclusion

The content of decision-making of condition-based maintenance in transmission lines was described. An idea for overhead transmission line maintenance decision-making ranking model and model solution was established through set pair analysis. The basis of the index in transmission line maintenance decision-making ranking and the calculation step of the overhead transmission line maintenance decision-making ranking model were provided. Two 500kV overhead transmission lines were analyzed by using the set pair analysis model established in this study. The maintenance decision-making ranking of the two transmission lines and another four unrepaired lines was calculated. The result is not only consistent with the actual maintenance status but also demonstrates the effectiveness of the proposed maintenance decision-making model.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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