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基于模糊TOPSIS方法的变压器维修策略

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摘 要:变压器维修策略的决策是一种涉及到量化指标和定性分析指标共存的混合多属性指标的决策问题.运用模糊理想解法(fuzzy TOPSIS)建立了变压器维修策略的模糊综合评价分析模型,来解决含有混合多属性指标决策问题.这种方法不仅可以对多台变压器的运行情况进行监视,通过利用计算相对贴近度来确定变压器的运行状态,进而确定变压器的维修策略,而且还可以通过专家系统对1台变压器的多种维修策略进行直接的判断与确定,通过精确的实数型指标值、区间数型的指标值和模糊数的指标值进行分类判断,给出多种维修策略下的取值情况,进而分析比较各个相对贴近度的大小,做出排序,决定选取哪种维修策略.通过实例验证此方法具有良好的决策效果.

关 键 词:电力变压器;模糊TOPSIS;混合多目标决策;维修策略;决策

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Transformer Maintenance Strategy Based on Fuzzy TOPSIS Method

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Abstract: Transformer maintenance strategy decision is a decision-making problem of hybrid multiple attribute index related to coexistence of quantitative indicators and qualitative indexes. The fuzzy comprehensive evaluation analysis model of the transformer maintenance strategy was set up by using fuzzy TOPSIS, and the decision-making problem of hybrid multiple attribute index was solved. Through calculating the relative closeness degree to determine the transformers operation status, the transformer maintenance strategy could be determined by using the proposed method. In addition, the proposed method not only can monitor transformers operation status, but also can directly determine the best one from various maintenance strategy for a transformer using the expert system. The index values of accurate real type, interval type and fuzzy number were classed and judged, then the relative closeness degree of various maintenance strategy was sorted through analysis and comparison, based on which it could be decided to choose which kind of maintenance strategy. The result of the example shows that the method has good effect on transformer maintenance strategy decision.

Key words: power transformer; fuzzy TOPSIS; hybrid multiple attribute decision making; maintenance strategy; decision-making

国内外对于电力变压器维修决策研究的最终目标和发展方向,目前集中在电力变压器的状态维修方面[1].

电力变压器故障诊断与状态维修决策模型的研究正向着多种方法混合的方向发展,以提高诊断及决策的正确率和准确度[2-5].本文利用基于

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理想点的多属性决策模型解决变压器状态维修策略的决策问题.

1 理想解法综合评价的理论基础

1.1 理想解法

理想解法(TOPSIS——technique for order by similarity to solution)是通过寻找多指标决策问题的正理想解和负理想解,作为评价各对象的判断依据[6-9].

1.2 理想解法评价的基本步骤

理想解法的基本思路如图 1 所示.

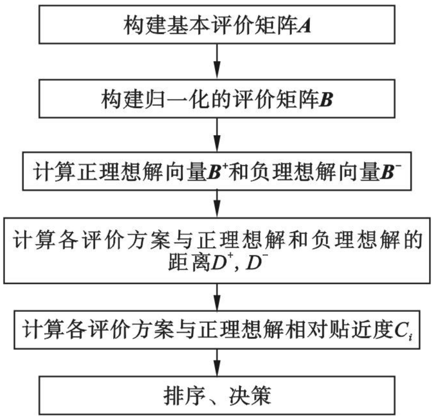

图 1 TOPSIS 法评价的基本流程图
Fig. 1 The basic flow chart of TOPSIS evaluation method

2 混合多属性理想解法

2.1 混合多属性(指标)决策问题的描述

设 $\boldsymbol{X}=\{x_1,x_2,\cdots,x_n\}$ 为 n 个方案的多属性决策问题的集合;$\boldsymbol{Y}=\{y_1,y_2,\cdots,y_m\}$ 为 m 个评价指标集合;$\boldsymbol{W}=\{w_1,w_2,\cdots,w_m\}$ 为 m 个指标的权重向量.

2.2 混合多属性(指标)决策问题的数值定义

定义 1 称 $a=[a^\alpha, a^\beta]$ 为区间数,其中 a^α, $a^\beta \in \mathbf{R}$,且 $a^\alpha < a^\beta$,$\mathbf{R}$ 上的全体闭区间记为 $\overline{\mathbf{R}}$.

定义 2 称 $\tilde{a}=(a^\alpha,a^\beta,a^\gamma)$ 为三角模糊数,如果它的隶属度函数为 $\mu_{\tilde{a}}(x):\mathbf{R}\to[0,1]$,即:

$$\mu_{\tilde{a}}(x)=\begin{cases}0, x\leqslant a^\alpha;\\ (x-a^\alpha)/(a^\beta-a^\alpha), a^\alpha<x\leqslant a^\beta;\\ (x-a^\beta)/(a^\gamma-a^\beta), a^\beta<x\leqslant a^\gamma;\\ 0, a^\gamma<x.\end{cases} \quad (1)$$

式中 $x\in\mathbf{R}$,$0\leqslant a^\alpha\leqslant a^\beta\leqslant a^\gamma\in\psi$,$\psi=[\alpha,\gamma]$ 为一个实数区间,当 $a^\alpha=a^\beta=a^\gamma$ 时,$\tilde{a}$ 为一个实数.

根据三角模糊数的定义,确定 9 种语言变量描述三角模糊数的取值如表 1 所示.

表 1 语意变量及其对应三角模糊数
Table 1 Semanteme variable and corresponding triangular-shape fuzzy number

序号	代码赋值	语意变量	三角模糊数
1	SL	超低	(0.0, 0.1 ,0.2)
2	EL	特低	(0.1, 0.2, 0.3)
3	VL	很低	(0.2, 0.3, 0.4)
4	L	低	(0.3, 0.4, 0.5)
5	S	一般	(0.4, 0.5, 0.6)
6	H	高	(0.5, 0.6, 0.7)
7	VH	很高	(0.6, 0.7, 0.8)
8	EH	特高	(0.7 , 0.8, 0.9)
9	SH	超高	(0.8, 0.9, 1.0)

定义 3 设 $a=[a^\alpha, a^\beta]$,$b=[b^\alpha, b^\beta]$ 是两个任意的区间数,则 $|a-b|=|a^\alpha-b^\alpha|+|a^\beta-b^\beta|$ 为区间数 a 到区间数 b 的距离.

定义 4 两个模糊数 $\tilde{a}=(a^\alpha,a^\beta,a^\gamma)$,$\tilde{b}=(b^\alpha,b^\beta,b^\gamma)$ 的距离记为 $d_{\mathrm{H}}(\tilde{a},\tilde{b})$,则有

$$d_{\mathrm{H}}(\tilde{a},\tilde{b})=\sqrt{\frac{(a^\alpha-b^\alpha)^2+(a^\beta-b^\beta)^2+(a^\gamma-b^\gamma)^2}{3}}.$$

2.3 混合多属性(指标)决策问题的原理与步骤

2.3.1 初始决策矩阵的规范化

效益型指标(I_1)和成本型指标(I_2)归一化的处理方法如下:

设 N_k 为决策矩阵 $\boldsymbol{A}=(a_{ij})_{n\times m}$ 的下脚标 i,j 的取值范围集合,$k=0,1,2,3$,其中 $N_0=\{1,2,\cdots,n\}$,$N_1=\{1,2,\cdots,h_1\}$,$N_2=\{h_1+1,h_1+2,\cdots,h_2\}$,$N_3=\{h_2+1,h_2+2,\cdots,m\}$.

1) 当 $i\in N_0$,$j\in N_1$ 时,b_{ij} 是精确实数:

$$b_{ij}=a_{ij}/\sqrt{\sum_{k=1}^{n}a_{kj}^2},(j\in \mathrm{I}_1 与 \mathrm{I}_2 两种类型). \quad (2)$$

2) 当 $i\in N_0$,$j\in N_2$ 时,b_{ij} 是区间数.

对于 I_1 类型有

$$b_{ij}^\alpha=\frac{a_{ij}^\alpha}{\sqrt{\sum_{k=1}^{n}(a_{kj}^\beta)^2}},b_{ij}^\beta=\frac{a_{ij}^\beta}{\sqrt{\sum_{k=1}^{n}(a_{kj}^\alpha)^2}}; \quad (3)$$

对于 I_2 类型有

$$b_{ij}^\alpha=\frac{1}{a_{ij}^\beta}/\sqrt{\sum_{k=1}^{n}(\frac{1}{a_{kj}^\alpha})^2},b_{ij}^\beta=\frac{1}{a_{kj}^\alpha}/\sqrt{\sum_{k=1}^{n}(\frac{1}{a_{kj}^\beta})^2}. \quad (4)$$

3) 当 $i\in N_0$,$j\in N_3$ 时,b_{ij} 是模糊数.

对于 I_1 类型有

$$b_{ij}^\alpha=\frac{a_{ij}^\alpha}{\sqrt{\sum_{k=1}^{n}(a_{kj}^\gamma)^2}},b_{ij}^\beta=\frac{a_{ij}^\beta}{\sqrt{\sum_{k=1}^{n}(a_{kj}^\beta)^2}},$$

$$b_{ij}^{\gamma} = \frac{a_{ij}^{\gamma}}{\sqrt{\sum_{k=1}^{n}(a_{kj}^{\alpha})^2}}. \quad (5)$$

对于 I_2 类型有

$$b_{ij}^{\alpha} = \frac{\frac{1}{a_{ij}^{\gamma}}}{\sqrt{\sum_{k=1}^{n}(\frac{1}{a_{kj}^{\alpha}})^2}}, \quad b_{ij}^{\beta} = \frac{\frac{1}{a_{kj}^{\beta}}}{\sqrt{\sum_{k=1}^{n}(\frac{1}{a_{kj}^{\beta}})^2}},$$

$$b_{ij}^{\gamma} = \frac{\frac{1}{a_{ij}^{\alpha}}}{\sqrt{\sum_{k=1}^{n}(\frac{1}{a_{kj}^{\gamma}})^2}}. \quad (6)$$

由上述公式得到规范化矩阵：

$$\boldsymbol{B} = (b_{ij})_{n\times m} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & a_{22} & \cdots & b_{2m} \\ \vdots & \vdots & & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix}.$$

2.3.2　规范化矩阵 $\boldsymbol{B} = (b_{ij})_{n\times m}$ 的加权矩阵形式 $\boldsymbol{R} = (r_{ij})_{n\times m}$ 的构成为 $r_{ij} = b_{ij}w_j$，w_j 为 b_{ij} 的权重.

2.3.3　确定正理想解向量 $\boldsymbol{X}^+$ 和负理想解向量 $\boldsymbol{X}^-$

1）当 r_{ij} 为精确实数型指标值时，令其正理想解为 V_j^+ 和负理想解为 V_j^-.

当指标为效益型指标时

$$V_j^+ = \max_{1\leqslant i\leqslant n} r_{ij}; V_j^- = \min_{1\leqslant i\leqslant n} r_{ij}, j\in N_1; \quad (7)$$

当指标为成本型指标时，

$$V_j^+ = \min_{1\leqslant i\leqslant n} r_{ij}; V_j^- = \max_{1\leqslant i\leqslant n} r_{ij}, j\in N_1. \quad (8)$$

2）当 r_{ij} 为区间数型指标值时，令其正理想解为 $[t_j^-, t_j^+]$ 和负理想解为 $[s_j^-, s_j^+]$.

当指标为效益型指标时，有

$$\left.\begin{aligned} t_j^+ &= \max_{1\leqslant i\leqslant n} r_{ij}^{\beta}, t_j^- = \max_{1\leqslant i\leqslant n} r_{ij}^{\alpha}, j\in N_2; \\ s_j^+ &= \min_{1\leqslant i\leqslant n} r_{ij}^{\beta}, s_j^- = \min_{1\leqslant i\leqslant n} r_{ij}^{\alpha}, j\in N_2. \end{aligned}\right\} \quad (9)$$

当指标为成本型指标时，有

$$\left.\begin{aligned} t_j^+ &= \min_{1\leqslant i\leqslant n} r_{ij}^{\beta}, t_j^- = \min_{1\leqslant i\leqslant n} r_{ij}^{\alpha}, j\in N_2; \\ s_j^+ &= \max_{1\leqslant i\leqslant n} r_{ij}^{\beta}, s_j^- = \max_{1\leqslant i\leqslant n} r_{ij}^{\alpha}, j\in N_2. \end{aligned}\right\} \quad (10)$$

3）当 r_{ij} 为模糊数型指标值时，令其正理想解为 $\tilde{a}_j^+$ 和负理想解为 $\tilde{a}_j^-$.

当指标为效益型指标时，有

$$\left.\begin{aligned} \tilde{a}_j^+ &= \max\{\tilde{r}_{1j}, \tilde{r}_{2j}, \cdots, \tilde{r}_{nj}\}, j\in N_3; \\ \tilde{a}_j^- &= \min\{\tilde{r}_{1j}, \tilde{r}_{2j}, \cdots, \tilde{r}_{nj}\}, j\in N_3. \end{aligned}\right\} \quad (11)$$

当指标为成本型指标时，有

$$\left.\begin{aligned} \tilde{a}_j^+ &= \min\{\tilde{r}_{1j}, \tilde{r}_{2j}, \cdots, \tilde{r}_{nj}\}, j\in N_3; \\ \tilde{a}_j^- &= \max\{\tilde{r}_{1j}, \tilde{r}_{2j}, \cdots, \tilde{r}_{nj}\}, j\in N_3. \end{aligned}\right\} \quad (12)$$

则正理想解向量 $\boldsymbol{X}^+$ 为

$$\boldsymbol{X}^+ = (V_1^+, V_2^+, \cdots, V_{h_1}^+, [t_{h_1+1}^-, t_{h_1+1}^+], \cdots, [t_{h_2}^-, t_{h_2}^+], \tilde{a}_{h_2+1}^+, \cdots, \tilde{a}_m^+);$$

负理想解向量 $\boldsymbol{X}^-$ 为

$$\boldsymbol{X}^- = (V_1^-, V_2^-, \cdots, V_{h_1}^-, [s_{h_1+1}^-, s_{h_1+1}^+], \cdots, [s_{h_2}^-, s_{h_2}^+], \tilde{a}_{h_2+1}^-, \cdots, \tilde{a}_m^-).$$

2.3.4　计算每个方案到理想解的距离

1）每个方案 x_i 到正理想解 $\boldsymbol{X}^+$ 的距离为

$$D_i^+ = d(x_i, \boldsymbol{X}^+) = \sqrt{(d_{i1}^+)^2 + (d_{i2}^+)^2 + \cdots + (d_{im}^+)^2}, \quad i = 1, 2, \cdots, n. \quad (13)$$

其中，

$$d_{ij}^+ = \begin{cases} (V_j^+ - r_{ij}), i = 1, 2, \cdots, n, j\in N_1; \\ |r_{ij}^- - t_j^-| + |r_{ij}^+ - t_j^+|, i = 1, 2, \cdots, n, j\in N_2; \\ d_{\mathrm{H}}(\tilde{r}_{ij}, \tilde{a}_j^+), i = 1, 2, \cdots, n, j\in N_3. \end{cases} \quad (14)$$

2）每个方案 x_i 到正理想解 $\boldsymbol{X}^-$ 的距离为

$$D_i^- = d(x_i, \boldsymbol{X}^-) = \sqrt{(d_{i1}^-)^2 + (d_{i2}^-)^2 + \cdots + (d_{im}^-)^2}, \quad i = 1, 2, \cdots, n. \quad (15)$$

其中，

$$d_{ij}^- = \begin{cases} (r_{ij} - V_j^-), i = 1, 2, \cdots, n, j\in N_1; \\ |r_{ij}^- - s_j^-| + |r_{ij}^+ - s_j^+|, i = 1, 2, \cdots, n, j\in N_2; \\ d_{\mathrm{H}}(\tilde{r}_{ij}, \tilde{a}_j^-), i = 1, 2, \cdots, n, j\in N_3. \end{cases} \quad (16)$$

2.3.5　计算每个方案的正理想解相对贴近度 C_i

计算公式为

$$C_i = \frac{D_i^-}{D_i^- + D_i^+}, i = 1, 2, \cdots, n. \quad (17)$$

按照 C_i 从大到小的顺序排列方案的优劣次序. 相对贴近度越高，方案越优；相对贴近度越低，方案越劣.

3　基于混合多属性理想解法变压器维修策略的研究

3.1　变压器维修策略的相对贴近度的选择标准

表 2 是变压器维修策略的选择标准.

表 2　变压器维修策略的选择标准

Table 2　Selecting standard of transformer repair strategy

相对贴近度	0.85～1.0	0.6～0.85	0.4～0.6	0.2～0.4	0.0～0.2
维修策略	延期维修	定期维修	监视运行	优先安排维修	立即停电维修

3.2　案例分析

采用文献[6]中的案例进行分析(见表 3).

表 3 某厂 4 台变压器的指标值
Table 3 The index value of 4 transformers in a factory

序号	评价指标						
	[H_2] μL/L	[总烃] μL/ L	绝缘电阻 /MΩ	直接损失/万元	维修费用/万元	可靠性	可维修性
1	10.3	34.5	8 000	[55,56]	[47,58]	特高	很高
2	12.2	12.33	5 500	[30,40]	[42,52]	超高	高
3	20.46	6.98	7 200	[49,60]	[50,60]	高	高
4	84.56	170.32	1 800	[35,45]	[45,55]	很高	一般
权重	0.10	0.13	0.15	0.08	0.06	0.25	0.23

注:1 ~3 台变压器的电压等级为 220 kV,第 4 台变压器电压等级为 35 kV.

决策矩阵 $\boldsymbol{A}(x_{ij})$ 为

$$\boldsymbol{A}(x_{ij})=\begin{bmatrix} 10.3 & 34.5 & 8\,000 & [50,80] & [50,60] & (0.7,0.8,0.9) & (0.6,0.7,0.8)\\ 12.2 & 12.33 & 5\,500 & [40,50] & [70,90] & (0.8,0.9,1.0) & (0.5,0.6,0.7)\\ 20.46 & 6.98 & 7\,200 & [49,60] & [78,89] & (0.5,0.6,0.7) & (0.5,0.6,0.7)\\ 84.56 & 170.32 & 1\,800 & [30,40] & [45,55] & (0.6,0.7,0.8) & (0.4,0.5,0.6) \end{bmatrix}.$$

将决策矩阵归一化为规范矩阵 $\boldsymbol{B}(x_{ij})$:

$$\boldsymbol{B}(x_{ij})=\begin{bmatrix} 0.116\,446 & 0.197\,871 & 0.654\,661 & [0.247\,411,0.523\,598] & [0.469\,107,0.682\,765] & (0.408\,52,0.527\,5,0.682\,288) & (0.426\,401,0.579\,324,0.792\,112)\\ 0.137\,926 & 0.070\,718 & 0.450\,079 & [0.395\,857,0.654\,498] & [0.312\,738,0.487\,689] & (0.466\,57,0.593\,44,0.758\,098) & (0.355\,335,0.496\,564,0.693\,103)\\ 0.231\,309 & 0.040\,033 & 0.589\,195 & [0.329\,881,0.534\,284] & [0.316\,252,0.437\,67] & (0.291\,61,0.395\,63,0.530\,668) & (0.355\,335,0.496\,564,0.693\,103)\\ 0.955\,988 & 0.976\,854 & 0.147\,299 & [0.498\,212,0.872\,664] & [0.511\,753,0.758\,628] & (0.349\,92,0.461\,57,0.606\,478) & (0.284\,268,0.413\,803,0.594\,089) \end{bmatrix}.$$

利用公式 $r_{ij}=b_{ij}w_j$ 将规范矩阵 $\boldsymbol{B}(x_{ij})$ 化为加权矩阵 $\boldsymbol{R}(r_{ij})$,

$$\boldsymbol{R}(r_{ij})=\begin{bmatrix} 0.011\,645 & 0.025\,72 & 0.098\,2 & [0.019\,793,0.041\,89] & [0.028\,146,0.040\,97] & (0.102\,06,0.131\,88,0.170\,572) & (0.098\,07,0.133\,245,0.182\,19)\\ 0.013\,793 & 0.009\,19 & 0.067\,51 & [0.031\,669,0.052\,36] & [0.018\,764,0.029\,26] & (0.116\,64,0.148\,36,0.189\,525) & (0.081\,73,0.114\,210,0.159\,41)\\ 0.023\,131 & 0.005\,2 & 0.088\,38 & [0.026\,390,0.042\,74] & [0.018\,975,0.026\,26] & (0.072\,9,0.098\,91,0.132\,667) & (0.081\,73,0.114\,210,0.159\,41)\\ 0.095\,599 & 0.126\,99 & 0.022\,09 & [0.039\,586,0.069\,81] & [0.030\,705,0.045\,52] & (0.087\,48,0.115\,39,0.151\,620) & (0.065\,38,0.095\,175,0.136\,64) \end{bmatrix},$$

确定正理想解 $\boldsymbol{X}^+$ 和负理想解 $\boldsymbol{X}^-$.

1) 对于精确实数值的正理想解 V_j^+ 与负理想解 V_j^- $(j=1,2,3)$ 有

$$V_j^+=\{0.011\,64,0.052,0.098\,2\},$$
$$V_j^-=\{0.095\,599,0.126\,99,0.022\,09\}.$$

[H_2][总烃]两个指标属于成本型指标,绝缘电阻属于效益型指标;

2) 对于区间数型指标值的正理想解 $[t_j^-,t_j^+]$ 和负理想解 $[s_j^-,s_j^+]$, $j=4,5$,由于直接损失和维修费用都属于成本型指标,所以有

$$t_j^+=\min_{1\le i\le n} r_{ij}^{\beta}=\{0.041\,888,0.026\,26\},$$
$$t_j^-=\min_{1\le i\le n} r_{ij}^{\alpha}=\{0.031\,669,0.018\,764\},$$
$$s_j^+=\max_{1\le i\le n} r_{ij}^{\beta}=\{0.069\,813,0.045\,518\},$$
$$s_j^-=\max_{1\le i\le n} r_{ij}^{\alpha}=\{0.039\,586,0.030\,705\}.$$

3) 对于模糊数型指标值的正理想解 $\tilde a_j^+$ 和负理想解 $\tilde a_j^-$, $j=6,7$,由于可靠性和可维修性都属于效益型指标,利用公式(11)有

$$\tilde a_j^+=\max\{\tilde r_{1j},\tilde r_{2j},\cdots,\tilde r_{nj}\}=\{(0.116\,642,0.143\,861,0.189\,525),(0.098\,07,0.133\,245,0.182\,187)\},$$
$$\tilde a_j^-=\min\{\tilde r_{1j},\tilde r_{2j},\cdots,\tilde r_{nj}\}=\{(0.072\,901,0.098\,907,0.132\,667),(0.065\,382,0.095\,175,0.136\,64)\}.$$

则正理想解向量 $\boldsymbol{X}^+$ 为

$$\boldsymbol{X}^+=(0.011\,64,0.005\,2,0.098\,2,[0.031\,669,0.0418\,88],[0.018\,764,0.026\,26],(0.116\,642,0.148\,861,0.189\,525),(0.098\,07,0.133\,245,0.182\,187));$$

负理想解向量 $\boldsymbol{X}^-$ 为

$X^- = (0.095\ 599, 0.126\ 99, 0.022\ 09, [0.039\ 586, 0.069\ 813], [0.030\ 705, 0.045\ 518], (0.072\ 901, 0.098\ 907, 0.132\ 667), (0.065\ 382, 0.095\ 175, 0.136\ 64))$.

根据式(13) ~ (14),每个方案 x_i 到正理想解 X^+ 的距离为 D^+,则

$$d_{ij}^+ = \begin{bmatrix} 0 & 0.020\ 52 & 0 & 0 & 0.024\ 088 & 0.061\ 768 & 0 \\ 0.002\ 15 & 0.003\ 99 & 0.030\ 69 & 0.022\ 348 & 0.003\ 001 & 0 & 0.019\ 56 \\ 0.011\ 49 & 0 & 0.009\ 82 & 0.007\ 452 & 0.000\ 211 & 0.050\ 305 & 0.019\ 56 \\ 0.083\ 95 & 0.121\ 79 & 0.076\ 1 & 0.047\ 718 & 0.031\ 198 & 0.033\ 536 & 0.039\ 13 \end{bmatrix},$$

$D_1^+ = \sqrt{(d_{11}^+)^2 + (d_{12}^+)^2 + \cdots + (d_{17}^+)^2} = 0.035\ 81.$

同理有

$D_2^+ = 0.043\ 05, D_3^+ = 0.056\ 54, D_4^+ = 0.183\ 24.$

每个方案 x_i 到负理想解 X^- 的距离为

$D_i^- = d(x_i, X^-) = \sqrt{(d_{i1}^-)^2 + (d_{i2}^-)^2 + \cdots + (d_{im}^-)^2}$, $i = 1, 2, \cdots, n.$

根据式(16)有

$$d_{ij}^- = \begin{bmatrix} 0.083\ 95 & 0.101\ 27 & 0.076\ 1 & 0.0477\ 18 & 0.007\ 111 & 0.033\ 536 & 0.021\ 11 \\ 0.081\ 81 & 0.117\ 8 & 0.045\ 42 & 0.025\ 370 & 0.028\ 197 & 0.050\ 305 & 0.009\ 44 \\ 0.072\ 47 & 0.121\ 79 & 0.066\ 28 & 0.040\ 266 & 0.030\ 988 & 0 & 0.009\ 44 \\ 0 & 0 & 0 & 0 & 0 & 0.016\ 768 & 0 \end{bmatrix},$$

则 $D_1^- = 0.164\ 3, D_2^- = 0.163\ 37, D_3^- = 0.164\ 77, D_4^- = 0.016\ 77.$

根据公式(17)计算每个方案的正理想解相对贴近度 C_i 有

$$C_1 = \frac{D_1^-}{D_1^- + D_1^+} = \frac{0.164\ 3}{0.164\ 3 + 0.035\ 81} = 0.821\ 04.$$

同理有

$C_2 = 0.791\ 44, C_3 = 0.744\ 5, C_4 = 0.083\ 84.$

通过计算可知:第一、二、三台变压器处于 0.6 ~ 0.8 的范围之内,维修策略选择定期维修,第四台变压器的相对贴近度处于 0.0 ~ 0.2 的范围之内,维修策略选择立即停电维修.

通过比较,本文多属性指标的变压器维修策略的确定与文献[6]的选择具有相同的效果,说明本文方法可行. 对于变压器 4,色谱数据诊断为高能量放电故障. 实际对该变压器进行吊罩检查,发现有载调压开关有一点烧灼痕迹,即有高能量放电故障发生,应该立即停电维修.

4　结　　论

1) 提出一种新的三角模糊数的定义方法;

2) 实现对多台变压器的运行情况进行监视,确定运行状态,进而确定变压器维修策略;

3) 可以通过专家系统对 1 台变压器的多种维修策略进行直接的判断与确定.

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