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ANALYTIC HIERARCHY PROCESS BASED FUZZY EVALUATION OF POWER NETWORK OPERATING SCHEMES

X. Niu
Shandong Electric Power Research Institute
Erhuan Nanlu, Jinan 250002, China
niuxs3701@126.com

H. Ye, Y. Liu
School of Electrical Engineering
Shandong University
73 Jingshi Avenue, Jinan 250061, China

ABSTRACT
Electromagnetic loop circuits may jeopardize the power system safety operation. A fuzzy comprehensive evaluation method based on analytic hierarchy process is presented in the paper for electric power network operating schemes. The analytic hierarchy process is used to analyze influencing factors, establish a hierarchical model and rank the influencing factors in order of importance. Performance indices and membership functions corresponding are presented to denote their contributions on overall objective. Quantitative evaluation results that considering various factors comprehensively are obtained by a two-level fuzzy comprehensive evaluation. Some simulation results of Shandong power system in China demonstrate the proposed method can be used to evaluate power network operating schemes.

KEY WORDS
Analytic hierarchy process, fuzzy comprehensive evaluation, electromagnetic loop circuits

1. Introduction

The electromagnetic loop circuits formed by parallel transmission lines of different voltage levels adding with transformers connecting them may jeopardize the power system safety operation. Due to disadvantages of the electromagnetic loop circuits, transmission system planners are inclined to find the best topological structure to avoid them. Available control actions are network switching, i.e., disconnecting of lower voltage level transmission lines and opening bus coupler breakers inside a substation. The benefits of the network after switching include improved distribution and easier manipulation of power flow, easier managing network divisions, lower transmission losses, reduced capacity of short circuit, easier coordinating protective relays and improved system stability [1]. The network switching has been proposed as a means to alleviate network overload in the 1980s [2] and has attracted a renewed interest recently [3]. The discrete feature of switching actions makes it very difficult to model them and design a systematic search method. On the other hand, the problem needs deal with both static power flow and transient stability simulations. There have been no reports on systematic evaluation methodologies and tools for the problem.

The analytic hierarchy process (AHP) methodology [4] is effective in modeling complex multi-objective problems hierarchically, thus provides a method to explicitly assess the influencing factors of the problems and has potential in quantifying the expertise. The properties of fuzzy comprehensive evaluation method make it a useful tool in considering various influencing factors containing fuzziness, and making comprehensive and overall evaluation [5]. In this paper, the electromagnetic loop circuit opening problem is modeled by influencing factors and performance indices with AHP and fuzzy logic. An evaluation method which comprehensively considers static security, transient stability and economy factors for electromagnetic loop circuit opening schemes is proposed to offer quantitative evaluation results. Some simulation results of Shandong power system in China demonstrate its effectiveness.

2. Fuzzy Comprehensive Evaluation

The process of the two-level fuzzy comprehensive evaluation can be outlined as following.

2.1 Weighting sets

The influenced factors can be classified into *m* categories. Each category forms a factor subset $\boldsymbol{B}_i$ (i=1, 2, …, m). A factor subset may contain *n* elements. The factor set $\boldsymbol{A}$ and factor subsets $\boldsymbol{B}_i$ can be written as

$$\begin{aligned} \boldsymbol{A} &= \{\boldsymbol{B}_1, \boldsymbol{B}_2, \ldots, \boldsymbol{B}_m\} \\ \boldsymbol{B}_i &= \{C_{i1}, C_{i2}, \ldots, C_{in}\} \end{aligned} \tag{1}$$

The AHP provides a scientific method for determination of weighting [4]. To obtain the weighting sets corresponding to the factor set and factor subsets that rank the elements in order of importance, pair-wise comparisons among elements in factor subsets are made after consulting experienced experts and engineers, resulting in a series of judgmental matrices. Take factor subset $\boldsymbol{B}_i$ for example, the corresponding judgmental matrix $\tilde{\boldsymbol{B}}_i$ can be formed as

$$\tilde{\boldsymbol{B}}_i = (c_{st})_{n\times n} \tag{2}$$

where c_{st} (s, t =1, 2, …, n) denotes the relative importance of s^{th} factor C_{is} over the t^{th} factor C_{it} in $\boldsymbol{B}_i$. One kind of the rating scales for pair-wise comparison can be found in [4].

The normalized weighting set $\boldsymbol{W}_i$ is generated from the judgmental matrix $\tilde{\boldsymbol{B}}_i$ as

$$\tilde{\boldsymbol{B}}_i \boldsymbol{W}_i = \lambda_{\max} \boldsymbol{W}_i \tag{3}$$

where $\lambda_{\max}$ is the largest eigenvalue. In order to avoid artificial errors and contradiction of different factors, consistency tests for judgmental matrices are needed.

In order to mark different levels of a problem, the evaluation results are classified into several levels by appropriate fuzzy linguistic variables. Assuming there are p levels, the evaluation result set $\boldsymbol{V}$ can be given as

$$\boldsymbol{V} = \{v_1, v_2, \cdots, v_p\} \tag{4}$$

where v_k (k=1, 2, …, p) is a linguistic variable which specifies the level of a evaluation result. Assigning each linguistic variable v_k a numeral, a numeric mark set $\boldsymbol{E}$ corresponding to the evaluation result set $\boldsymbol{V}$ is obtained, viz. $\boldsymbol{E}=\{e_1, e_2, \ldots, e_p\}$.

2.2 Two-level fuzzy comprehensive evaluation

The first level fuzzy comprehensive evaluation is made for each factor subset $\boldsymbol{B}_i$(i=1, 2, …, m). The evaluation result vector of factor subset $\boldsymbol{B}_i$ can be obtained from the composition of its weighting set $\boldsymbol{W}_i$ and single-factor evaluation matrix $\boldsymbol{R}_i$ as

$$\tilde{\boldsymbol{S}}_i = \boldsymbol{W}_i \circ \boldsymbol{R}_i = (S_{i1}, S_{i2}, \cdots, S_{ip}) \tag{5}$$

where $\boldsymbol{R}_i = (r_{ijk})_{n\times p}$, its element r_{ijk} denotes the degree of membership μ to which the j^{th} factor C_{ij} in $\boldsymbol{B}_i$ belongs to the k^{th} linguistic variable v_k in evaluation result set $\boldsymbol{V}$, i.e.,.

$$\begin{aligned} &\mu : \boldsymbol{B}_i \to \mu(\boldsymbol{V}) \\ &C_{ij} | \to (r_{ij1}, r_{ij2}, \ldots, r_{ijp}) \end{aligned} \tag{6}$$

The element S_{ik} in $\tilde{\boldsymbol{S}}_i$ can be expressed as

$$S_{ik} = \sum_{j=1}^{n} w_{ij} r_{ijk} \tag{7}$$

After obtaining the evaluation result vector for each factor subset, i.e., $\tilde{\boldsymbol{S}}_i$ (i=1, 2, …, m), the single-factor evaluation matrix of the second level fuzzy comprehensive evaluation can be formed as

$$\boldsymbol{R} = \left[r_{ik}\right]_{m\times p} = \begin{bmatrix} \tilde{\boldsymbol{S}}_1 \\ \tilde{\boldsymbol{S}}_2 \\ \cdots \\ \tilde{\boldsymbol{S}}_m \end{bmatrix} = \begin{bmatrix} \boldsymbol{W}_1 \circ \boldsymbol{R}_1 \\ \boldsymbol{W}_2 \circ \boldsymbol{R}_2 \\ \cdots \\ \boldsymbol{W}_m \circ \boldsymbol{R}_m \end{bmatrix} \tag{8}$$

Then the second level fuzzy comprehensive evaluation result vector $\boldsymbol{S}$ is produced as

$$\boldsymbol{S} = \boldsymbol{W} \circ \boldsymbol{R} = (S_1, S_2, \cdots, S_p) \tag{9}$$

where $\boldsymbol{W}$ is the weighting set corresponding to the factor set $\boldsymbol{A}$.

Finally, the priority of fuzzy comprehensive evaluation for the evaluated problem can be generated by the "weighted-average" method as

$$N = \sum_{k=1}^{p} S_k e_k \Big/ \sum_{k=1}^{p} S_k \tag{10}$$

3. Electromagnetic Lop Circuit Evaluation

3.1 Hierarchical model

In order to study operating schemes of electromagnetic loop circuits, an interconnected and interactive hierarchical structure with an overall goal at the top followed by criteria hierarchy and then indices hierarchy is established by using AHP and shown in Fig.1.

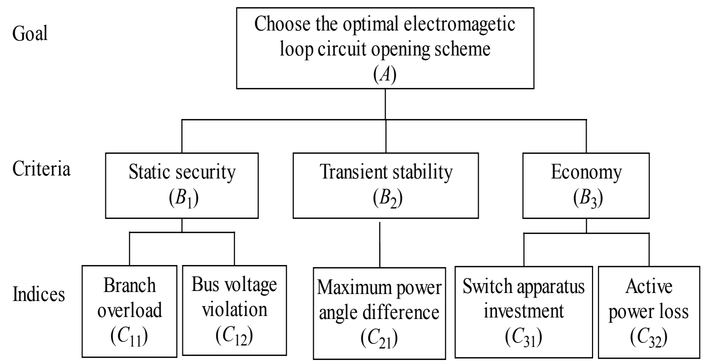

Fig. 1 Hierarchical model

The goal of electromagnetic loop circuit opening is to obtain the optimal opening scheme among candidates. As shown in Fig.1, the criteria hierarchy includes all criteria that influence the overall objective. These criteria are static security, transient stability and economy. Indices hierarchy is generated by extending each of the three criteria to concrete indices. These indices are introduced as following.

Power system static security can be represented by constraints that the system should satisfy under given contingencies, i.e., power flows and bus voltage magnitudes are kept within acceptable limits. Branch overload index and bus voltage violation index therefore are introduced.

System response to a severe transient disturbance involves large excursion of generator rotor angles due to the change of the network structure. Following a disturbance, the degree of transient stability/instability can be evaluated by the maximum difference of generator rotor angles. Therefore, maximum power angle difference is defined as the transient stability index.

By switching lines and bus couplers strategically, the lower voltage level divisions operate independently and connected to the neighboring divisions only via higher voltage level power grid. The short circuit currents of single divisions are reduced. Thus, the cost of the switch apparatus investment cuts down. Additionally, power flows will transfer from the lower voltage level lines to the higher ones and active power losses may lessen. Here, switch apparatus investment index and active power loss index are simply taken to reflect the economy criterion.

3.2 Performance indices

Five performance indices corresponding to the five indices in Fig.1 are developed in the following. Their respective membership functions are established and presented in next subsection.

A security index related to branch overload is defined similarly as [6]

$$PI_P = \sum_{\alpha} w_{P,l} \left(\frac{S_l}{S_l^{\max}} \right)^2 \tag{11}$$

where $\boldsymbol{\alpha}$ is the branch set, S_l and $S_l^{\max}$ are load and limit in MVA of branch l, $w_{P,l}$ is branch weighting factor.

The definition of bus voltage violation index is based on as

$$PI_V = \sum_{\beta} w_{V,i} \left(\frac{V_i - V_i^{sp}}{\Delta V_i^{\lim}} \right)^2 \tag{12}$$

where $V_i^{sp} = (V_i^H + V_i^L)/2$, $\Delta V_i^{\lim} = (V_i^H - V_i^L)/2$. β is the bus set, V_i is the voltage magnitude at bus i, $w_{V,i}$ is bus voltage weighting factor. V_i^H and V_i^L are high and low voltage limits at bus i which are set by engineers indicating how much they wish to limit a bus voltage from changing on one outage case.

Maximum power angle difference index is defined as

$$PI_\theta = \sum_{\gamma} \left\{ Max\left|\theta_i - \theta_j\right| \right\} \Big/ 180 \tag{13}$$

where $\boldsymbol{\gamma}$ is a pre-selected list of contingencies, θ_i and θ_j are power angles in degree of two arbitrary generators after the fault is cleared in a contingency analysis.

Switch apparatus investment index is defined as

$$PI_I = \sum_{\beta} w_{I,k} \left(\frac{I_k}{I_k^{\max}} \right)^2 \tag{14}$$

where β is the bus set, I_k is the three phase short circuit current at bus k, $I_k^{\max}$ is the breaking current limit of the breaker at bus k, $w_{I,k}$ is short circuit weighting factor.

Active power loss index PI_{loss} is measured by the system active power loss under a certain candidate opening scheme.

3.3 Membership function

Five variables excellent(E), good(G), average(A), fair(F) and poor(P) are assigned to uniformly partition the universes of discourse of each performance index. For simplicity, half-trapezoidal and triangular shaped membership functions for each performance index are developed. Thus, the differences between the membership functions of each performance index are minimum value, the values with unity membership and the maximum value for each fuzzy linguistic variable.

Taking the branch overload index PI_P for instance, its membership functions are shown in Fig.2, where λ_1 to λ_5 are five unity membership values by which the closed interval [λ_1, λ_5] is linearly divided. Similar functions are applied to other performance indices.

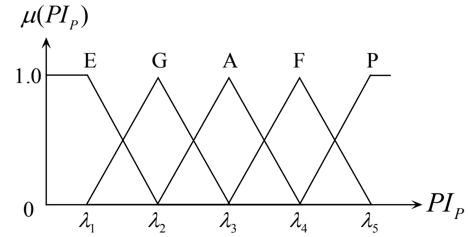

Fig. 2 Membership function of PI_P

4. Simulation Results

The proposed fuzzy comprehensive evaluation method is tested on a practical power system of Shandong province in China. Some results of north part of the power system are listed out as an example to illustrate the application of the proposed method.

In the north part of Shandong power system as shown in Fig.3, Huade power plant is the main source. It has four 300MW generating units (#1~#4) and two 600MW generating units (#5~#6). Units #1~#3 are connected to the 220 kV bus and the remains are connected to the 500 kV bus. This regional network connected with other networks via Jinan and Zibo substations. There exist several 500 kV-220 kV electromagnetic loop circuits in this regional power system, such as: Huade500-Huade220-Linyi220-Jinan220-Jinan500-Huade500, Huade500-Huade220-Shuangmiao220-Dayang220-Binzhou220-Binzhou500-Huade500, Huade500-Huade220-Zhongsuo220-Xiaozhen220-Zibo220-Zibo500-Jinan500-Huade500.

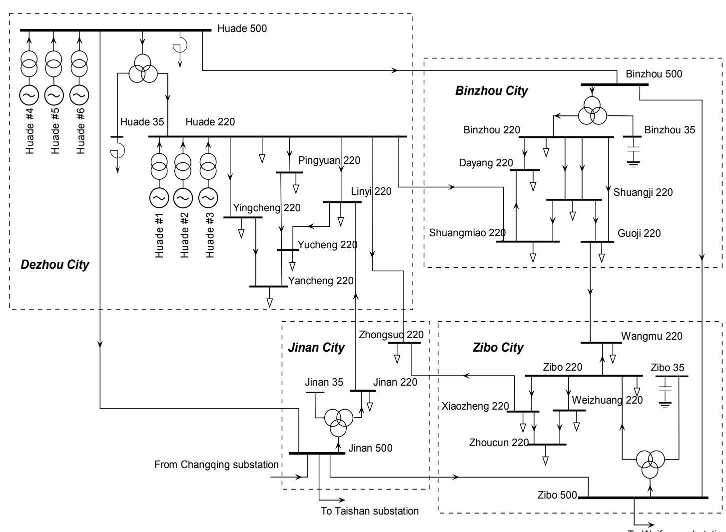

Fig. 3 Diagram of north part of Shandong power system

Geographically, Linyi, Shuangmiao, Zhongsuo and Xiaozhen substations locate in Dezhou, Binzhou, Jinan and Zibo administrative areas, respectively. According to the constraints for switching described in Section 3.4, the following schemes are considered for these electromagnetic loop circuits:

Scheme 1: Jinan220 - Linyi220 transmission line is disconnected at Linyi substation;

Scheme 2: Huade220 - Shuangmiao220 transmission line is disconnected at Shuangmiao substation;

Scheme 3: Zhongsuo220 - Xiaozhen220 transmission line is disconnected at Zhongsuo substation;

Scheme 4: The 220kV bus coupler breaker at Linyi substation is opened. The load at this substation is supplied by 220 kV bus of Jinan substation.

Among these schemes, scheme 1 and scheme 4 can open the electromagnetic loop circuit between Dezhou and Jinan. Scheme 2 and scheme 3 can open the electromagnetic loop circuits between Dezhou and Binzhou as well as Dezhou and Zibo, respectively.

The judgmental matrices corresponding to the factor set and factor subsets are determined and their corresponding weighting set are obtained as, $\boldsymbol{W}$={0.633, 0.261, 0.106}, $\boldsymbol{W}_1$={0.500, 0.500}, $\boldsymbol{W}_2$={1.000} and $\boldsymbol{W}_3$={0.750, 0.250}, respectively.

For simplicity, the weighting factor $w_{P,l}$ is taken to be 1.0 for all branches, while both $w_{V,i}$ and $w_{I,k}$ are set to be 1.0 for all buses. The computational results for PI_P, PI_V, PI_θ, PI_I and PI_{loss} within each scheme are tabulated in Table 1. It can be found that values of PI_P and PI_V vary with different operating conditions while values of PI_θ are almost unchanged. The unity membership values, λ_1, λ_2, λ_3, λ_4 and λ_5 for each of the five performance indices are listed in Table 2, by which the computational results tabulated in Table 1 can be fuzzified. Thus, the single-factor evaluation matrices for each of the three criteria, i.e., $\boldsymbol{R}_1$, $\boldsymbol{R}_2$, and $\boldsymbol{R}_3$ are obtained.

Table 1 Computational results

Operating condition	PI_P	PI_V	PI_θ	PI_I	PI_{loss}	N
Base	344.93	2311.02	19.67	12.31	341.38	0.434
Scheme 1	364.06	2433.24	19.51	7.48	340.95	0.245
Scheme 2	343.17	2429.93	19.66	7.41	343.12	0.387
Scheme 3	344.65	2351.12	19.72	7.53	340.66	0.414
Scheme 4	341.20	2196.66	19.50	7.48	341.89	0.740

Table 2 Unity membership values

Performance index	λ_1	λ_2	λ_3	λ_4	λ_5
PI_P	341	343	345	347	349
PI_V	2195	2255	2315	2375	2435
PI_θ	19.1	19.3	19.5	19.7	19.9
PI_I	7.0	7.2	7.4	7.6	7.8
PI_{loss}	340	341	342	343	344

After two-level fuzzy comprehensive evaluation, the column N in Table 1 exhibits the obtained priority of each opening scheme. It is clear that scheme 4 is optimal.

From the weighting set $\boldsymbol{W}$, it can be found that static security has the highest weighting among the three criteria that influence the main goal. It can be concluded that the scheme that has better static security, the priority of that scheme may be higher. In summary, the result in the choice of scheme 4 is consistent with the qualitative judgment by experienced experts.

Additionally, it can be seen from the case study that, once determining the hierarchy model and the weighting sets corresponding to the influencing factors for electromagnetic loop circuit opening problem, the remains that need determining are membership function related parameters, i.e., λ_1, λ_2, λ_3, λ_4 and λ_5. However, these parameters are case-dependent. If simple method is utilized to partition the universe of discourse of each performance, e.g. linear/uniform partition, the parameters can be easily determined. Thus, the proposed method is easy for practical application.

5. Conclusion

Combining AHP with fuzzy comprehensive evaluation, a evaluate technique for power network operating scheme is presented in this paper, aim to help system planners optimally open electromagnetic loop circuits. It does not take part of but comprehensively takes all of the static security, transient stability and economy factors into consideration using the fuzzy logic theory. The main difficulties that may lead confusion and uncertainties, i.e., determining the hierarchy model and weighting sets are solved by AHP, which quantifies the expertise and experiences of the experts and engineers. The remains that need determining are parameters relating to membership functions. However, these parameters are case-dependent and can be easily determined. Therefore the proposed method is easy for practical application though it contains expertise. The simulation results of the practical Shandong power system show that the proposed method can provide the decision makers with intrinsic information to guide opening the electromagnetic loop circuits.

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