Research Article

Security Assessment of Coal Mine Power Grid Voltage Based on an Improved AHP-FCE

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Received 30 December 2021; Accepted 5 March 2022; Published 25 April 2022

1. Introduction

The power supply quality and reliability of coal mine power grids directly affect all aspects of coal mine production. The load of the coal mine power grid is mostly large rotating machinery driven by electric motors [1–3], and the voltage level of the power grid directly affects the starting and normal operation of the electric motors. The startup of large motors in the mine will cause voltage fluctuations in the coal mine power grid, which will have a certain impact on the safe operation of the power grid. Additionally, as one of the main parameters used to measure the power supply quality of the power grid, the stability of the voltage has an important influence on the safe operation of coal mine power grids and production equipment.

Coal mine power grids belong to the end of the power system, and most of them are single-ended radial grids. Power supply lines are generally laid along roadways. With the continuous deepening of mining, the power supply distance is constantly expanding. At the same time, coal mine loads are mostly large asynchronous motors with a low power factor. Large-capacity loads such as underground hoists and coal shearsers have a greater impact on the power grid, which can easily cause low voltage at the end of the underground power supply. The low-voltage phenomena of a coal mine power grid can generally be divided into low-voltage loads and low-voltage faults. A low-voltage load refers to the phenomenon in which the power supply line loss is too large due to the heavy load carried by the line and a large amount of reactive power is transmitted between systems, which makes the voltage at the end of the line too low. A low-voltage fault means that the voltage is too low due to a fault in the coal mine power supply network. Due to the narrow space of the coal mine, the power supply cables are mostly laid along the roadways, and they are vulnerable to external forces such as squeezing and collision, which damages the insulation of the cables and causes a short circuit. This will cause a significant drop in voltage and seriously affect the normal production of the mine.
The coal mine power supply network performs remote monitoring of the power supply, which can complete the remote measurement, remote signaling, and remote control functions of the coal mine power grid. However, the monitoring system displays only the voltage and active and reactive power of each point in the power grid. The displayed data cannot be analyzed, and the low-voltage level and the impact of the voltage level on the operation of the power grid cannot be accurately determined so that the operating status and the possible faults of the power grid cannot be accurately evaluated. Therefore, it is impossible to adjust the grid structure and parameters in time to prevent the occurrence of major accidents.

To prevent excessive voltage fluctuations from threatening the safe operation of coal mine power grids, it is necessary to determine the current operating status and voltage development trend of the power grid in time. This paper selects the coal mine power grid voltage as one of the main technical parameters to measure the operating state of the power grid. By using the real-time grid structure parameters and real-time power flow distribution data provided by the power grid monitoring system, the improved analytic hierarchy process and fuzzy comprehensive evaluation (AHP-FCE) is used to construct a fuzzy comprehensive evaluation matrix to comprehensively evaluate the current voltage level, which can analyze the voltage development trend and give early warnings regarding the voltage situation of the coal mine power grid.

The structure of this paper is as follows: Section 2 provides a literature review and summarizes the previous research results; Section 3 introduces the traditional AHP-FCE method and proposes improved algorithms; Section 4 describes the specific problems that need to be solved when the evaluation model is applied to an example; Section 5 introduces the detailed numerical work in the evaluation model; the conclusions of this paper are given in Section 6.

2. Literature Review

Voltage stability assessment is considered by many scholars to be an extremely important research topic in voltage situation assessment research. Voltage stability refers to the ability of the power system to keep all bus voltages stable after a disturbance [4–6]. An increasing number of scholars believe that voltage instability is the main phenomenon that causes the voltage amplitude to gradually decrease and eventually leads to the collapse of the system voltage [7–9]. The voltage collapse event may occur within a few seconds to a few minutes after a major event. The influence of voltage instability usually occurs initially in a local area and then extends to the entire system [10, 11]. In addition, it may cause unexpected cascading failures until the power system eventually loses power. Therefore, the power system essentially requires a clear voltage instability state and early warning capabilities. The voltage stability index is the key to evaluating voltage stability. Chaowanan Jamroen [12] proposed an early warning indicator of voltage instability based on synchrophasor data. This index is obtained by observing the sensitivity of V-Q. It can be used to evaluate voltage instability and impending voltage collapse. Xie Xiong [13] proposed a new method for evaluating the voltage stability of distribution networks. This method directly derives the voltage correction value on the imaginary axis of each node through the power flow algorithm and then substitutes the derived imaginary axis correction value into the simplified voltage equation to obtain the quadratic equation of the real axis voltage correction value. The root discriminant of the quadratic equation is used as the new voltage stability index of the distribution network. S. Aboreshaid [14] presented a contingency enumeration-based approach to evaluate the voltage stability of a power system. The proposed approach includes the selection and evaluation of contingencies, the classification of contingencies according to selected failure criteria, and the accumulation of voltage stability indices. Xiaoyuan Xu proposed a global sensitivity analysis (GSA) method to perform a priority ranking of renewable energy variabilities that will affect the voltage stability of power systems [15]. Additionally, the stochastic response surface method is adopted in GSA to improve the computational efficiency of the proposed evaluation method. Joao A. S. Neto [16] presented a new method for voltage analysis of islanded microgrids using the energy function method. The energy function allows the direct stability evaluation of the system operating points, taking into account the variation of loads, the photovoltaic intermittence, and the charging and discharging of energy storage systems under predefined conditions. Qianhong Wu [17] proposed an algorithm for the bidirectional evaluation of the voltage stability margin (VSM) with large photovoltaic (PV) power penetration.

However, the above studies reflect the voltage situation of the system from a single side. In fact, the voltage situation is related to many factors, such as changes in load, changes in generator output power (including exit from operation), line failures, and various control methods. Environmental conditions also play a role that cannot be ignored. Therefore, to give the voltage situation analysis results more accurately and quickly, an index system must be established that reflects the voltage situation from different angles, and the voltage situation must be measured from multiple sides.

Against this background, AHP-FCE is considered. AHP-FCE has been applied to decision-making and evaluation issues in many fields. Reference [18] combined fuzzy data quantification and the AHP-FCE method to establish the mechanical performance evaluation (MPE) model of the actuator. Reference [19] established a comprehensive evaluation index system including 19 indicators and proposed a comprehensive method for evaluating the legal risks of high-tech small and medium-sized enterprises based on the AHP-FCE model. Reference [20] applied the AHP-FCE model to evaluate the importance of compound compressor units. Research has shown that this method is feasible and provides guidance for the design, manufacture, production, and maintenance of reciprocating compressors from a more impartial and objective perspective. Reference [21] proposed an AHP-FCE-based health evaluation method for metal roofs and applied it to an actual roof health monitoring system. Reference [22] used the AHP-FCE method to evaluate an intelligent learning environment and used the
GA-BP algorithm to improve the AHP-FCE model, which made the evaluation process easier and improved the fault tolerance. Reference [23] proposed a multilevel fuzzy comprehensive evaluation model based on improved AHP-FCE for network security situation assessment. However, the comparison judgment matrix in the AHP method is given subjectively based on the opinions of experts, which is too subjective and has a great influence on the final evaluation result. Therefore, we introduce an interval judgment matrix to replace the comparison judgment matrix, and we search for the deterministic matrix with the best consistency in the interval judgment matrix to determine the best weight vector. Such an improved AHP method can not only retain the subjectivity of the expert to the greatest extent but also improve the objectivity of the weight vector.

3. Evaluation Models and Principles

In this section, we introduce the detailed calculation steps and principles of the adopted method (AHP-FCE). In addition, the improved algorithm for the AHP is introduced in this section. The main contribution of this section is to propose an improved algorithm based on the traditional AHP method to improve the objectivity of the weight vector. To the best of our knowledge, this is a novel method of improving the AHP. Specifically, the improved AHP is used to set the weight of the index, and FCE is used to construct the evaluation matrix.

3.1. AHP Method. The AHP is a decision analysis method combining qualitative and quantitative approaches proposed by the American operations researcher T.L. Satty in the 1970s. It is a way of modeling and quantifying the decision process of a decision-maker in a complex system, which is suitable for solving the problem of combining qualitative and quantitative approaches. The specific steps of the AHP are as follows:

Step 1. Establish a hierarchical structure.

The hierarchical structure can usually be divided into a target layer, element layer, and indicator layer. The target layer represents the purpose of solving the problem; the element layer represents the intermediate links involved in reaching the expected target; and the indicator layer represents the various measures, policies, and programs to be selected to solve the problem.

Step 2. Construct an n-order comparison judgment matrix.

\[
A = \begin{bmatrix}
    a_{11} & a_{12} & \cdots & a_{1n} \\
    a_{21} & a_{22} & \cdots & a_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix},
\]

(1)

where \(a_{ij}\) presents the element in the i-th (i = 1, 2, ..., n) row and j-th (j = 1, 2, ..., n) column of matrix A. When i = j, there is \(a_{ij} = 1\); otherwise, there are \(a_{ij} > 0\) and \(a_{ji} = 1/a_{ij}\). The relative importance \(a_{ij}\) is usually expressed by a 1–9 scale and its reciprocal, which indicates the degree of importance of an element at this level relative to the previous element. The specific meaning is shown in Table 1.

In the hierarchical structure, each element and the next-level element dominated by the element constitute a subarea. For each element in the area, the expert consultation method is used to construct \(k\) such comparison judgment matrices, that is, \(A_1, A_2, \ldots, A_k\). The comparison judgment matrix indicates the importance of the relevant elements of this level for a certain element of the upper level.

Step 3. Weight vector calculation.

The calculation of weights usually includes the following steps.

Normalize each column of \(A\) to obtain the elements of the normalized matrix \(\bar{A}\). Therefore, the elements \(\bar{a}_{ij}\) of \(\bar{A}\) can be expressed as

\[
\bar{a}_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}.
\]

(2)

Sum the normalized judgment matrix line by line, as shown in (3):

\[
\bar{\omega}_i = \sum_{j=1}^{n} \bar{a}_{ij}.
\]

(3)

By normalizing \(\bar{\omega}_i\), the weight of the index \(\omega_i\) can be obtained as follows:

\[
\omega_i = \frac{\bar{\omega}_i}{\sum_{i=1}^{n} \bar{\omega}_i}.
\]

(4)

Then, we can obtain the desired weight vector \(W = [\omega_1, \omega_2, \ldots, \omega_n]^T\).


To examine whether the weight vector is reasonable, it is necessary to input the calculation result of the weight vector into the formula below for the consistency test. The consistency index includes the consistency test index CI, the average random consistency index RI, and the random consistency ratio CR. The variables CI, RI, and CR can be calculated or obtained as follows.

The consistency test index CI of the comparison judgment matrix can be calculated by

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1},
\]

(5)

where \(\lambda_{\text{max}}\) is the maximum eigenvalue of the comparison judgment matrix and it can be calculated as

\[
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} (AW)_i \omega_i,
\]

(6)

where \((AW)_i\) is the i-th element of the product of \(A\) and \(W\).

The average random consistency index RI of the multilevel matrix is related to the order \(n\) of the matrix, and its index values are shown in Table 2.
3.2. FCE Method. Comprehensive evaluation refers to a comprehensive evaluation of events that contain multiple influencing factors. In the process of evaluation, the quantitative value of the influencing factors exhibits fuzziness. Fuzzy comprehensive evaluation applies the principle of fuzzy transformation and membership degrees, considers the factors related to the evaluated objects, and comprehensively evaluates them.

Step 1. Establish a set of evaluation factors.
Assuming that the evaluation object has m evaluation indicators, we can use $U = \{u_1, u_2, \ldots, u_m\}$ to denote them. For a multilevel evaluation index system, the evaluation factors can be divided into first-level evaluation factors according to their properties, the first-level evaluation factors can be divided into the corresponding second-level evaluation factors, and so on. This process is written as $U = U_1 \cup U_2 \cup \ldots \cup U_n$, where

$$U_i = \{u_{i1}, u_{i2}, \ldots, u_{im}\}, \quad U_i \cap U_j = \emptyset$$  \hspace{0.5cm} (8)

Step 2. Determine the comment set.
This paper divides the voltage situation levels into 6 different levels, which can be indicated by $V = \{v_1, v_2, \ldots, v_6\}$. The detailed definitions of the different levels are shown in the next section.

Step 3. Establish the fuzzy membership matrix.

Step 4. Select the weight vector.
The weight vector of the criterion layer with respect to the target layer of the coal mine power grid security situation is $W$, and the weight vectors of the index layer with respect to the criterion layer are $W_1$, $W_2$, and $W_3$. The specific values of the weight vectors can be directly calculated by the AHP method.

Step 5. Calculate the comprehensive evaluation matrix.
A fuzzy synthesis algorithm is applied to the index layer to perform fuzzy synthesis, $B_i = W_i \cdot R_i$, and the secondary evaluation matrix of the target layer is obtained. Normalizing $B_1$, $B_2$, and $B_3$, we can obtain $B_1'$, $B_2'$, and $B_3'$; then, we can form a first-level fuzzy membership matrix $R = [B_1', B_2', B_3']$. Finally, a first-level evaluation matrix $B = W \cdot R$ will be obtained.

Step 6. Determine the voltage safety level.
$B$ is the judgment vector of the voltage safety level. To make a correct judgment regarding the voltage safety level, further analysis and calculation of $B$ are needed. We normalize $B$ to obtain $B'$ and then use the weighted average method to analyze and calculate $B'$ to obtain the accurate voltage safety level. The weighting algorithm is

$$b = \frac{\sum_{j=1}^{m} b_j v_j}{\sum_{j=1}^{m} b_j},$$  \hspace{0.5cm} (10)

where $b_j$ is an element in judgment vector $B$, $v_j$ is an element in the comment, and $v_j = \{6, 5, 4, 3, 2, 1\}$.
3.3. Improved AHP ALGORITHM. When using AHP-FCE for security situation assessment, it is necessary to determine the relative importance of each index, and its mathematical expression is the weight vector. In this paper, we replace the comparison judgment matrix with an interval judgment matrix and modify the interval judgment matrix to improve its consistency. We search for the deterministic matrix with the best consistency in the revised interval judgment matrix to determine the best weight vector. This method not only retains the subjectivity of expert evaluation but also improves the objectivity of the weight vector.

3.3.1. Related Definitions. Interval judgment matrix: suppose the subscript set of $n$ elements is $I = \{1, 2, \cdots, n\}$ and that the relative importance between element $i$ and element $j$ is $a_{ij}$. Denote the interval judgment matrix as $\bar{A} = (\bar{a}_{ij})_{n \times n}$, and the interval number $\bar{a}_{ij}$ as $[a_{ij}^L, a_{ij}^U]$; $\bar{a}_{ij} = [1/a_{ij}^L, 1/a_{ij}^U]$, where $a_{ij}^L \leq a_{ij}^U$ and $a_{ij}^L$ and $a_{ij}^U$ are the upper and lower limits of each element of the converged interval matrix. This paper adopts a judgment matrix on the scale of 1–9.

Random matrix: define the matrix $A = (a_{ij})_{n \times n}$, where $a_{ij} \in [a_{ij}^L, a_{ij}^U]$ and the random number $a_{ij}$ is generated from the interval $[a_{ij}^L, a_{ij}^U]$ according to a uniform distribution probability.

Satisfactory consistency: it is known that the consistency ratio of judgment matrix $A$ is $CR(A) = [\lambda_{max}(A) - n/(n-1)RI] / \lambda_{max}(A)$. When $CR < 0.1$, the judgment matrix $A = (a_{ij})_{n \times n}$ is considered to have satisfactory consistency. Here, $\lambda_{max}(A)$ is the maximum eigenvalue of judgment matrix $A$, and $RI$ is the average random consistency index. The values are shown in Table 1.

Degree of consistency of the interval matrix: define $\gamma$ as the degree of consistency of the interval matrix. Suppose that $Q$ random matrices are generated from the interval matrix $\bar{A}$, and the number of matrices with satisfactory consistency is $p$; then, $\gamma = p/Q$.

3.3.2. Improved Algorithm Module. The improved AHP algorithm is divided into 3 submodules, namely, the interval matrix consistency judgment submodule, the interval matrix element adjustment submodule, and the best deterministic matrix acquisition submodule.

The workflow design of the improved algorithm is as follows:

Step 1. Calculate the consistency degree of a given interval matrix through the interval matrix consistency degree judgment module to obtain the consistency degree value.

Step 2. If the degree of the consistency value is greater than the threshold, go to Step 3; otherwise, interact with the expert, adjust the interval number elements in the interval matrix, and go to Step 1.

Step 3. Calculate the best deterministic matrix based on the optimized interval matrix to obtain this matrix and use it as the basis for solving the weight vector.

The processing method and process of each submodule are described in detail as follows:

(a) The submodule for judging the consistency of the interval matrix.

For the interval judgment matrix given by the expert, $Q$ random matrices are generated according to the uniform distribution probability, the consistency ratio $CR_k (k = 1, 2, \cdots, Q)$ of the generated random matrix is calculated in turn, and the number of random matrices with a satisfactory degree of consistency is $p$. Then, the degree of consistency of the interval matrix is $\gamma = p/Q$. The larger $\gamma$ is, the better the consistency of the interval matrix is; the smaller $\gamma$ is, the worse the consistency of the interval matrix is. In this paper, $Q = 100$.

(b) The adjustment submodule of the interval matrix elements.

When the consistency of the interval matrix $\gamma$ is less than a certain threshold, some elements in the interval matrix need to be adjusted. The specific design process is as follows:

Step 1. Cross out the elements in the h-th row and h-th column of the interval matrix to form n subinterval matrices of order n-1 and calculate the consistency $\gamma_h (h = 1, 2, \cdots, n)$ of the n subinterval matrices $\overline{A}_h$.

Step 2. If the degrees of consistency $\gamma_k$ and $\gamma_{k-1}$ of the subinterval judgment matrix $\overline{A}_h$ and $\overline{A}_{h-1}$ are greater than the degrees of consistency of the other subinterval judgment matrices, it can be seen that the common interval element $[a_{h_1}^L, a_{h_1}^U], [a_{h_2}^L, a_{h_2}^U]$ between row $h_1$ and column $h_1$ and row $h_2$ and column $h_2$ of the original interval judgment matrix $\bar{A}$ has a greater influence on the consistency of $\bar{A}$. Therefore, it is necessary to exchange opinions with experts to adjust the interval element $[a_{h_1}^L, a_{h_1}^U], [a_{h_2}^L, a_{h_2}^U]$.

Step 3. Transfer to the interval matrix consistency judgment module and continue to calculate the consistency of the adjusted interval judgment matrix. Since the elements in row $h$ and column $h$ in the interval matrix are crossed out, this is equivalent to isolating the row $h$ and column $h$ elements from the remaining elements. If the consistency of the subinterval matrix is greatly improved, it means that the elements in row $h$ and column $h$ have a negative impact on the consistency of the original interval judgment matrix, so experts need to be asked to adjust the corresponding elements to improve the consistency of the interval matrix (Figure 1).

(c) The submodule for obtaining the best deterministic matrix.

The optimal deterministic matrix is obtained based on the optimized interval judgment
matrix. The submodule includes two processes: interval matrix convergence and optimal deterministic matrix searching. The specific process is designed as follows:

(1) Convergence of the interval matrix. In Step 1, to meet the needs of the global search for the optimal deterministic matrix as well as possible, the ratio of each deterministic number in the randomly generated deterministic matrix that falls into the left half of the interval element of the original interval matrix is $\alpha$, and it satisfies $0.5 - \eta < \alpha < 0.5 + \eta$ (in this paper, $\eta = 0.05$), which can prevent the elements of the randomly generated deterministic matrix from being concentrated in a certain half-interval of the original interval judgment matrix and avoid a local optimal search.

Step 1. Based on the optimized interval judgment matrix, $R$ deterministic matrices are randomly generated according to the probability of uniform distribution.

Step 2. Calculate the consistency ratio of the $R$ deterministic matrices $CR_i$ ($i = 1, 2, \cdots, R$) and obtain the first $\omega$ deterministic matrices with a small consistency ratio through sorting to form the $t$-th matrix cluster, which is denoted as $Cluster\_matrix\_t$.

Step 3. The new interval is integrated with the same position elements of different matrices in the matrix cluster, and then the upper and lower limits of each interval element in the new interval judgment matrix are obtained. When $i = j$, $a_{ij} = 1$; when $i \neq j$, $a_{ij} = \min\{a_{ij}^L, a_{ij}^U, \cdots, a_{ij}^{'L}\}$, $a_{ij}^U = \max\{a_{ij}^U, a_{ij}^{'U}, \cdots, a_{ij}^{'L}\}$, and $\pi_{ji} = \frac{1}{1+a_{ij}^L} \frac{1}{1+a_{ij}^U}$.

Step 4. Transfer the newly generated interval judgment matrix to Step 1 until the sum of the interval lengths of the elements of the interval matrix $|a_{ij}^{'} - a_{ij}^{''}| (i, j = 1, 2, \cdots, n)$ does not exceed 10% of the sum of the interval lengths of the elements of the original interval judgment matrix.

(2) The optimization of the deterministic matrix.

Step 1. Take the converged interval matrix as the input and record it as $Input\_matrix$. First, a deterministic matrix $M_0$ is initialized, and each element of the deterministic matrix is $a_{ij} (i, j = 1, 2, \cdots, n)$. When $i = j$, $a_{ij} = 1$; when $1 < j < n$ and $1 < i < j$ (the upper triangular part of the matrix), $a_{ij} = (a_{ij}^L + a_{ij}^U)/2$; and when $1 < i < n$ and $1 < j < i$, $a_{ij} = 1/a_{ji}$. For this certainty matrix, calculate its consistency ratio $CR_0$ as the initial consistency ratio.

Step 2. Randomly generate a deterministic matrix from $Input\_matrix$, record it as $M_i (i = 1, 2, \cdots, k)$, calculate its consistency ratio $CR_i$, and compare it with $CR_0$; if $CR_i < CR_0$, then $CR_0 = CR_i$; otherwise, keep $CR_0$ and $M_0$ unchanged.

Step 3. Adjust each element in each generated deterministic matrix according to equations (4) and (5):

$$v = \tau \times v + c \times \lambda \times (\psi - \zeta)$$

$$\zeta = \zeta + v,$$

where $v$ is the optimization speed, $\tau$ is the search speed coefficient, and $\tau$ is used to adjust the search speed. $c$ is the cognitive factor, and usually, $c = 2$; $\lambda$ is a random number between 0 and 1; $\psi$ is an element in the deterministic matrix with the smallest current consistency ratio; and $\zeta$ represents an element in the current deterministic matrix.

Define $v_{max} = \min\{a_{ij}^L, a_{ij}^U\} (i \neq j, i, j = 1, 2, \cdots, n)$. If $v > v_{max}$, then $v = v_{max}$; if $v < -v_{max}$, then $v = -v_{max}$. If $\zeta \in [a_{ij}^L, a_{ij}^U]$, then $\zeta$ does not need to be adjusted; if $\zeta < a_{ij}^L$, then $\zeta = a_{ij}^L$; and if $\zeta > a_{ij}^U$, then $\zeta = a_{ij}^U$. Take the initial value of $v$ to be 0, and $v_0$ corresponds to the elements in the initial deterministic matrix $M_0$ in Step 1; $\zeta_0$ corresponds to the elements of the deterministic matrix that are generated randomly for the first time in Step 2.

Step 4. Repeat Steps 2 to 3 for $k$ iterations.

After optimizing the deterministic matrix, the deterministic matrix with the smallest consistency ratio is finally obtained. On this basis, the weight vector can be obtained by using the eigenvector method. The traditional AHP algorithm obtains the comparative judgment matrix by comparing the relative importance between the two indicators, which will lead to the stronger subjectivity of experts; as a result, the evaluation results may not be consistent with the actual situation. In the improved AHP algorithm, we replace the comparison judgment matrix with the interval judgment matrix and search for the best certainty matrix in the interval judgment matrix, which greatly reduces the subjectivity of the comparison judgment matrix and makes the acquisition of the weight vector more objective.

4. Empirical Application of the Evaluation Model

In accordance with the requirements of the AHP, we analyzed the main factors affecting the voltage level of the coal mine power grid, determined the interval judgment matrix of each layer, and obtained the best weight vector through the improved AHP algorithm. The membership degree matrix of each layer for the target layer is established by fuzzy theory, and the optimal weight vector and the
membership degree matrix are fuzzily synthesized to obtain a comprehensive judgment of the coal mine power grid voltage level.

4.1. Selection of the Voltage Situation Evaluation. The power supply voltage level of the coal mine power grid is affected by many factors. The selection and acquisition of the evaluation indicators play an important role in the voltage warning level. The factors that can accurately and sensitively reflect the operating status of the grid voltage should be selected as the voltage evaluation indicators. Based on references [24, 25] and soliciting the opinions of on-site staff, this paper selects 14 indicators as the voltage situation assessment indicators to construct a voltage situation assessment analysis model, as shown in Figure 2.

In Figure 2, \( x_{11} \) is the index used to evaluate the possibility of chain exit of the line, \( x_{12} \) is the index used to evaluate the maximum instantaneous sudden voltage after the line is broken, \( x_{13} \) is the index used to evaluate the available resources of voltage recovery after the line is broken, \( x_{14} \) is the index used to evaluate the active power imbalance generated after the line fault, and \( x_{15} \) is the index used to evaluate the reactive power imbalance generated after the line fault. \( x_{21} \) is the overall compliance level index of the system, \( x_{22} \) is the load rise rate index, \( x_{23} \) is the load rise rate index, \( x_{24} \) is the PV curve slope index of the monitoring node, \( x_{31} \) is the index used to evaluate the degree of voltage stability, \( x_{32} \) is the index used to evaluate the extent of the maximum voltage over the upper limit, \( x_{33} \) is the index used to evaluate the extent of the maximum voltage over the lower limit, \( x_{34} \) is the index used to evaluate the active power loss of the system, and \( x_{35} \) is the index used to evaluate the degree of maximum voltage drop of the system.

4.2. Confirmation of the Comment Set. We have analyzed the impact of different voltage levels on the operation of the power grid in the actual operation of the coal mine power grid. The voltage situations are divided into 6 different levels, and different colors are used to indicate the different levels of the voltage situation, which intuitively reflects the current situation in terms of the voltage status. The voltage situation level of the coal mine power grid can be expressed as

\[
V = \{v_1, v_2, \ldots, v_6\}
\]

\[
= \{\text{black, red, orange, yellow, blue, green}\}
\]

\[
= \{6, 5, 4, 3, 2, 1\}. \quad (12)
\]

The colors indicating the tension of the voltage from high to low are black, red, orange, yellow, blue, and green. Each color represents a different voltage level, as shown in the following.
Black (6) means that the system power is severely unbalanced, the voltage is severely low, and some of the load cannot operate normally. If no measures are taken, the operation of the grid under this voltage state will cause a large-scale blackout or the removal of a large amount of load.

Red (5) means that the voltage level is low, the system power has a serious imbalance, some high-power loads cannot start normally, and more loads need to be removed to restore the voltage to normal.

Orange (4) indicates that the system voltage is too low, and the power is unbalanced. If the necessary measures are not taken, the voltage will continue to be low, and a small amount of unimportant loads or system reactive power compensation will need to be removed to restore the system to normal.

Yellow (3) indicates that the voltage situation is not too serious. The voltage is slightly low. Only proper regulation is needed to restore the system voltage to normal. Otherwise, the system voltage will be further reduced, and the operating state will deteriorate further, which may cause the line voltage to be too low and the equipment to be unable to operate normally.

Blue (2) indicates that the system voltage is normal, but the load level is high, and a small load disturbance in the power grid will affect the voltage level.

Green (1) indicates that the system voltage is completely normal, the load level is low, and the power margin is large; the grid can continue to operate in this state.

The above 6 colors represent the current voltage status, and an alarm is raised to the grid operator. The colors show the possible development trend of the grid if necessary measures are not taken, and they can be used as a basis for the monitoring system to adjust the grid operating parameters and structure.

4.3. Membership Function Calculation. When calculating the fuzzy relationship matrix from the factor set to the evaluation set, different membership functions are used for different evaluation indicators. For indicators that are difficult to quantitatively express, the membership function is determined by the method of fuzzy statistical expert evaluation. For evaluation indicators that can be calculated quantitatively, according to fuzzy mathematics, different membership functions are set. The optimal and worst critical values $p$ and $q$ of the indicator are determined according to the actual situation of the grid planning and operation. Then, 4 equidistant points $c_1, c_2, c_3$, and $c_4$ are inserted into $(p, q)$, and the membership degree of the evaluation index $x_{ij}$ belonging to the level $V_s$ is obtained as

![Figure 2: Voltage situation assessment analysis model.](image-url)
A convergent, is obtained as follows: After 7 iterations, the interval judgment matrix, which is as 0.6. After calculation, interval is judged, and the consistency degree threshold is set indicator convergence, according to the optimal deterministic matrix $5.1. Weight Vector Calculation. For the four subindicators ($x_{21}$, $x_{22}$, $x_{23}$, and $x_{24}$) subordinate to the load monitoring indicator $x_2$ in the factor layer, experts are asked to provide an interval judgment matrix for the relative importance of these four subindicators: $x_{ij}^{(1)} = \begin{cases} 1, & \lambda < p \\ (c_1 - \lambda)/r, & p \leq \lambda < c_1, \\ 0, & \lambda \geq c_1 \end{cases}$ (13)
$x_{ij}^{(2)} = \begin{cases} 0, & \lambda < c_{i-2}, \\ (\lambda - c_{i-2})/r, & c_{i-2} \leq \lambda < c_{i-1}, \\ (c_1 - \lambda)/r, & c_{i-1} \leq \lambda < c_i, \\ 0, & \lambda \geq c_i \end{cases}$ (14)
$x_{ij}^{(3)} = \begin{cases} 0, & \lambda < c_4, \\ (\lambda - c_4)/r, & c_4 \leq \lambda < q, \\ 1, & \lambda \geq q \end{cases}$ (15)
where $r = (q - p)/5; \lambda$ is the actual value of indicator $x_{ij}; c_0 = p; and c_i = q, i = 2, 3, 4, 5.$

5. Numerical Work

5.1. Weight Vector Calculation. For the four subindicators ($x_{21}$, $x_{22}$, $x_{23}$, and $x_{24}$) subordinate to the load monitoring indicator $x_2$ in the factor layer, experts are asked to provide an interval judgment matrix for the relative importance of these four subindicators:

$$A^0 = \begin{bmatrix} 1 & [3, 4] & [3, 5] & [3, 5] \\ [1, 1] & 1 & [1, 2] & [2, 5] \\ [\frac{1}{4}, \frac{1}{3}] & [1, 2] & 1 & [\frac{1}{3}, 1] \\ [\frac{1}{5}, \frac{1}{3}] & [\frac{1}{5}, \frac{1}{3}] & [1, 1] & 1 \end{bmatrix}.$$

According to the improved algorithm of the AHP, first, the consistency of the judgment matrix of the fourth-order interval is judged, and the consistency degree threshold is set as 0.6. After calculation, $\gamma = 0.76 > 0.6$, indicating that the consistency degree of the judgment matrix in this region meets the requirements, and there is no need to interact with experts for adjustment. This matrix is taken as the input matrix of the optimal deterministic matrix submodule. First, the interval judgment matrix converges, and $a = 1$ is taken. After 7 iterations, the interval judgment matrix, which is convergent, is obtained as follows:

$$A^1 = \begin{bmatrix} 1 & [3.210, 3.463] & [3.653, 4.000] & [4.202, 4.417] \\ [0.289, 0.312] & 1 & [0.934, 0.953] & [2.029, 2.040] \\ [0.250, 0.274] & [1.049, 1.070] & 1 & [0.894, 0.905] \\ [0.226, 0.238] & [0.490, 0.493] & [1.104, 1.119] & 1 \end{bmatrix}.$$ (17)

On the basis of the interval judgment matrix after convergence, according to the optimal deterministic matrix optimization algorithm, the optimal deterministic matrix can be obtained by taking the optimal number of searches $k = 1000$:

$$A^\text{best} = \begin{bmatrix} 1 & 3.300679 & 3.874924 & 4.261778 \\ 0.300351 & 1 & 0.942991 & 2.032611 \\ 0.259102 & 1.057097 & 1 & 0.899372 \\ 0.233799 & 0.490148 & 1.109949 & 1 \end{bmatrix}.$$ (18)

The consistency ratio of $A^\text{best}$ is $CR = 0.022591 < 0.1$; therefore, this matrix is a satisfactory consistency matrix. According to the calculation rules of the weight vectors, the weight vectors of the four subindexes subordinate to the load monitoring index $x_2$ can be obtained as follows:

$$W_2 = [0.555665, 0.178134, 0.144072, 0.122129].$$ (19)

In the same way, the weight vector of the line monitoring index and voltage monitoring index can be obtained:

$$W_1 = [0.237052, 0.156435, 0.257127, 0.208824, 0.140562],$$ (20)

$$W_3 = [0.213754, 0.167325, 0.184457, 0.205732, 0.228732].$$ (21)

The weight vector of the element layer can be obtained by the traditional AHP weight calculation method:

$$W = [0.1637, 0.5390, 0.2973].$$ (22)

5.2. Fuzzy Evaluation Matrix. The real-time power flow distribution data provided by the coal mine power monitoring system are shown in Table 3. Combined with the grid structure parameters, the 14 voltage situation evaluation indicators in Figure 1 are calculated. For each factor in the indicator layer, according to the grid operating structure diagram and the real-time grid power flow data of the grid monitoring system, we calculate the real-time power flow distribution data and the possible active and reactive voltage changes when grid N-1 fails and then perform fuzzy processing. For the factors that cannot be calculated quantitatively, fuzzy statistics and the experience of operators are used to judge their possible estimated values. The load monitoring index and voltage monitoring index value can be provided by the power grid monitoring system. By querying the real-time database and historical database of the power grid monitoring system, we calculate the real-time power flow distribution data and the possible active and reactive voltage changes when grid N-1 fails and then perform fuzzy processing. For the factors that cannot be calculated quantitatively, fuzzy statistics and the experience of operators are used to judge their possible estimated values. The load monitoring index and voltage monitoring index value can be provided by the power grid monitoring system. By querying the real-time database and historical database of the power grid monitoring system, the historical maximum and minimum values of each factor can be obtained. By comparison with the current value, the index value can be obtained. For example, we can calculate the overall load level of the system $x_{21}$, query the historical database of the monitoring system to obtain the minimum load value of the system $F_{\text{min}}$, perform the coal mine load statistical calculation, use the maximum load factor and the load demand system to obtain the maximum load value $F_{\text{max}}$, and calculate the overall load level of the system $x_{21}$.
\[ x_{21} = \frac{F}{F_{\text{max}} - F_{\text{min}}} \]  \hspace{1cm} (23)

The calculation of the other index values is similar. For the calculation method of the voltage stability margin, please refer to references [26–29] to obtain the evaluation index value and then perform fuzzy processing on the index value. From Table 3 and formulas (13)–(23), the index value of the index layer and its fuzzy membership evaluation matrix can be calculated as shown in Table 4.

### 5.3. Voltage Safety Level Judgment

Apply the fuzzy synthesis algorithm to the index layer to perform fuzzy synthesis, \( B_1 = W \cdot R_1 \), and obtain the secondary judgment matrix for the target layer:

\[ B_1 = \begin{bmatrix} 0.02745 & 0.22621 & 0.47989 & 0.12397 & 0.08722 & 0.05525 \\ 0.08060 & 0.21378 & 0.46713 & 0.07654 & 0.14407 \\ 0.13894 & 0.07481 & 0.09776 & 0.19713 & 0.20987 & 0.28148 \end{bmatrix} \]

 Normalize \( B_1, B_2, \) and \( B_3, \) obtain \( B'_1, B'_2, \) and \( B'_3 \), form a first-level fuzzy evaluation matrix \( R = [B'_1, B'_2, B'_3], \) and obtain a first-level evaluation matrix:

\[ B = \begin{bmatrix} 0.0458 & 0.1035 & 0.2249 & 0.3353 & 0.1187 & 0.1718 \end{bmatrix}. \]  \hspace{1cm} (24)

According to (9), the current voltage safety level is \( b = 3.107 \), so the current voltage is at the yellow warning level, which indicates that the power supply voltage level of the coal mine power grid is slightly low. If the power grid operates in this state, the load will fluctuate slightly. The voltage level will drop further, and normal operation will not be possible. The evaluation result is consistent with the actual voltage level of the coal mine power grid displayed by the coal mine power monitoring system. Through further analysis of the cause of the low voltage, it is found that the power factor of the grid is low. Operating experience has shown that if appropriate adjustments are made, such as switching reactive power compensation devices on and off or adjusting the grid structure, the system can be restored to normal and healthy operation; otherwise, the grid operation status is likely to deteriorate further, which will cause accidents and seriously affect the safe production of coal mines.

### 5.4. Future Work

Safety assessment methods have always been a hot spot in the field of coal mine safety production. Although the improved AHP-FCE algorithm can accurately assess the safety of coal mine voltage levels, there are still many methods worth trying. With the rise of artificial

<table>
<thead>
<tr>
<th>Bus name</th>
<th>Bus voltage amplitude (kV)</th>
<th>Active power (kW)</th>
<th>Reactive power (kvar)</th>
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<tr>
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<td>7202</td>
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<tr>
<td>Waste shaft II</td>
<td>5.82</td>
<td>4870</td>
<td>4730.4</td>
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<tr>
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<td>5.84</td>
<td>2095</td>
<td>1900.5</td>
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<tr>
<td>Ground west substation II</td>
<td>5.69</td>
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<td>4440.85</td>
</tr>
<tr>
<td>Second-level substation II</td>
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<td>2698</td>
<td>1781</td>
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<tr>
<td>Second-level substation III</td>
<td>5.72</td>
<td>3267</td>
<td>3444</td>
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<tr>
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<td>5.79</td>
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</tr>
<tr>
<td>Underground central substation II</td>
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<td>2938</td>
<td>3216</td>
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<tr>
<td>Dark inclined shaft substation</td>
<td>5.78</td>
<td>775.1</td>
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<tr>
<td>Bottom substation I</td>
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<td>984.4</td>
<td>1064.2</td>
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<tr>
<td>Bottom substation II</td>
<td>5.61</td>
<td>1358.1</td>
<td>1791.1</td>
</tr>
<tr>
<td>Bottom well fan</td>
<td>5.90</td>
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<td>311.5</td>
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</table>

<table>
<thead>
<tr>
<th>Index factor set</th>
<th>Index value</th>
<th>Fuzzy evaluation matrix</th>
</tr>
</thead>
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<td>-10.0000</td>
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</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>( R_2 )</td>
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</tr>
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<tr>
<td></td>
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<tr>
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<td>0 0 0 0 0.3100 0.6900</td>
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<tr>
<td></td>
<td>0.2580</td>
<td>0 0 0 0 0 0.3900 0.6100</td>
</tr>
</tbody>
</table>

Table 3: The real-time power flow distribution data.

Table 4: Fuzzy membership evaluation matrix.
intelligence in recent years, we will combine security assessment methods with artificial neural networks, deep learning, and other technologies to make security assessment methods more accurate and intelligent.

6. Conclusion

The voltage safety level assessment of coal mine power grids plays an important role in ensuring the safe operation of coal mine power grids. Large-scale underground motors have high voltage level requirements. When the power supply voltage level of a coal mine grid is low, some large-scale motors may not start normally, which will cause shocks to the grid during startup, affect voltage stability, and cause grid accidents. Therefore, it is necessary to evaluate the voltage level of the coal mine power grid. In order to solve the problem of too strong subjectivity of experts in the traditional AHP algorithm, an improved AHP algorithm is proposed in this paper. The concept of the interval judgment matrix is proposed. By replacing the comparison judgment matrix with the interval judgment matrix, the optimal certainty matrix is searched in the interval judgment matrix, which will greatly reduce the subjectivity of the comparison judgment matrix and make the acquisition of the weight vector more objective. The evaluation results will also be more accurate. The real-time power flow distribution data of the coal mine power grid monitoring system are used to evaluate the voltage safety level, and different colors are used to indicate the different evaluation levels of the voltage. The results are consistent with the actual voltage level, indicating that the improved AHP-FCE method is effective and feasible for the evaluation of the coal mine power grid voltage safety level. Coal mine power grid voltage safety level assessment can improve the monitoring level of coal mine power grids, analyze and warn of the possible future state of the grid voltage under the current operating state of the power grid, and adjust the grid structure and line load configuration in time before power grid accidents. Overall, it can improve the security and reliability of the power supply of the coal mine power grid and has value in promotion and application.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


