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Research of Wildfire Danger Rating and Forecasting Based on an Improved Efficacy Coefficient Method

Jing Zhou[1,*] and Weiqing Ma[2]

[1]*School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China;* [2]*The Department of Information Technology Shanxi Yangquan Electric Power Corporation, Yangquan, 045000, China*

Abstract: With the continuously expanding scale of the electric power grid in recent years, wildfire has been one of the main disasters which threaten the security of operation of power grid. Therefore, accurate, reliable, professional wildfire rating and forecasting along transmission lines has become a big challenge for entrepreneurs in power grid. In this paper, the combination of factors in power grid and environmental factors to cause wildfire was discussed firstly, and a wildfire rating and forecasting indicator system was established. Then a wildfire rating and forecasting model and a five-grade rating standard were built. Finally, according to the actual situation in a northern province in China, 8 data sets were used to test the method. The prediction result is largely identical to the actual situation of power grid operation, and shows that this method is more professional and more valid compared with other methods.

Keywords: Analytic hierarchical process, efficacy coefficient method, rating and forecasting, transmission line wildfire.

1. INTRODUCTION

With the rapid economic development in China, the electric power industry has also developed quickly. Power grid scale is growing, and more power transmission lines cross through forest regions. Meanwhile, with the continuous development of hydropower resources in the southwest, more and more hydropower plant transmission lines go across high mountains and hills which are covered by forests. Once wildfire breaks out, it easily spreads to the transmission lines nearby to cause trip accidents, most of which would be reclosing failures so to cause blackouts. When more than one transmission lines in one region are affected by forest fires simultaneously, the safe and stable operation of power grid would be threatened or even blackout accident in a larger area would be caused. Accurate prediction on wildfires danger rating can help to find out the vital monitored and detected areas to enable transmission line patrol personnel to get accurate forecasting information of wildfires in time, and to enhance fire source control there. Then accidents of power outrages caused by forest fires could decrease [1].

In this paper, firstly the combination of factors in power grid and environmental factors to cause wildfire was discussed, and a wildfire rating and forecasting indicator system was established. Then a wildfire rating and forecasting model and a five-rank rating standard were built. Finally, according to the actual situation in a northern province in China, 8 data sets were used to test the method. The prediction result is largely identical to the actual situation of power grid operation, and shows that this method is more professional and more valid compared with other traditional methods.

2. THE PRINCIPLE OF EFFICACY COEFFICIENT METHOD

The efficacy coefficient method is a quantitative evaluation method, which can reflect multiple indicators and analyze them comprehensively. For each evaluation indicator, a satisfied value is taken as the upper limit and a disallowed value as the lower limit. Then the degree of achieving the satisfied value for each indicator could be calculated to determine its efficacy coefficient. Finally a composite assessment value could be given by the weighted evaluation, which can determine the composite status of the researched object [2, 3]. The evaluation process is as following.

2.1. Establishment of Evaluation Indicator System

To reflect the general features of efficacy coefficient method, evaluation indicators should be representative, complementary and non-redundant so that they could reflect the overall status of the evaluation target as far as possible.

2.2. The Allowable Range of Each Evaluation Indicator

Satisfied value refers to the optimal value under present conditions, and disallowed value is the minimum value. The allowable range varies from the allowable value to the disallowed value.

2.3. Calculation of Single Efficacy Coefficient of Each Indicator

In this assessment indicator system based on efficacy coefficient, there are four kinds of variables for each indicator [4]: when the larger the actual indicator value is, the larger the single efficacy coefficient is, the indicator is called a maximum-type variable; when the smaller the actual index value is, the larger the single efficiency coefficient is, the indicator is called a minimum-type variable; when the single efficacy coefficient reaches the maximum at a point, the indicator is called a stable-type variable; and when the single efficacy coefficient is the largest all through an interval, the indicator is called a interval-type variable.

The formulas of the single efficacy coefficient of the four variables above are showed as following respectively.

1) The single efficacy coefficient of maximum-type variable

$$f_{1i} = \begin{cases} \dfrac{x_i - x_i^h}{x_i^s - x_i^h} \times 40 + 60, x_i < x_i^s \\ 100, x_i \geq x_i^s \end{cases} \quad (1)$$

where f_{1i} the single efficacy coefficient of the ith maximum-type is index; x_i is the ith $(i = 1,2,\cdots,m)$ actual value of indicator; x_i^h is the satisfied value of the ith indicator; x_i^s is the disallowed value of the ith indicator.

2) The single efficacy coefficient of minimum-type variable

$$f_{2i} = \begin{cases} \dfrac{x_i^h - x_i}{x_i^h - x_i^s} \times 40 + 60, x_i > x_i^s \\ 100, x_i \leq x_i^s \end{cases} \quad (2)$$

3) The single efficacy coefficient of stable-type variable

$$f_{3i} = \left(1 - \frac{|x_i - x_i^h|}{|x_i^s - x_i^h|}\right) \times 40 + 60 \quad (3)$$

4) The single efficacy coefficient of interval-type variable

$$f_{4i} = \begin{cases} \left(1 - \dfrac{x_{min} - x_i}{x_{min} - x_{min}^s}\right) \times 40 + 60, x_i < x_{min} \\ 100, x_{min} \leq x_i \leq x_{max} \\ \left(1 - \dfrac{x_i - x_{max}}{x_{max}^h - x_{max}}\right) \times 40 + 60, x_i > x_{max} \end{cases} \quad (4)$$

where x_{max} is the upper limit of interval-type variable and $x_{\min}$ is the lower limit; $x_{\max}^h$ is the disallowed value for upper limit and generally set as twice as the mean value of evaluation indicator in all intervals; $x_{\min}^s$ is the disallowed value for the lower limit and generally set as half as the mean value of evaluation indicator in all intervals, f_{4i} is the single efficiency coefficient value of the ith interval-type variable.

2.4. Determination of the Weight Coefficient of Each Indicator and Calculation of the Overall Efficacy Coefficient of the Evaluated Object

$$D = \prod_{i=1}^{m} f_i^{\omega_i} \quad (5)$$

where D is the overall efficacy coefficient, f_i is the single efficacy coefficient of the ith evaluation indicator, ω_i is the normalized weight coefficient of the ith evaluation indicator.

3. TRANSMISSION LINE WILDFIRE DANGER RATING AND FORECASTING MODEL

3.1. Analysis on Impact Factors on Transmission Line Wildfire and the Establishment of the Evaluation Indicator System

Transmission line wildfires generally refer to fires occurring nearby or along the corridor of transmission lines, which possibly cause failures in power grid so to threaten the safe of transmission lines. Wildfire rating and forecasting for transmission line is different from the one for common forest fire, which pay more attention on predicting the risk for transmission line failures. Therefore, impact factors in two sides should be taken into account: factors to possibly cause wildfires (B1) and factors to indicate the threatened degree of the power grid by wildfires (B2).

B1 includes three aspects [5]: The first is the combustible, which is the basic condition for wildfires. Every organic matter in forest would be the combustible. The second is the source of fire from nature or human. The third is the matched weather conditions for wildfires, for instance, rainfall (R), maximum temperature (T), minimum air relative humidity (H) and wind velocity (V) significantly impact the occurrence, spread or extinguish of wildfires [6].

B2 includes two aspects: the highest voltage grade (U) and power grid density (G) in test areas. G is defined as the length of transmission lines beyond the voltage grade of 110KV within unit area (1km2). B2 represent the degree of threat from wildfires, and help entrepreneurs in power grid make decisions of emergency disposal for transmission line wildfires. Based on the above analysis, the indicator system for transmission line wildfires rating and forecasting is built and showed in Table **1**.

In the above table, except C and S, all other indicators could be quantified by monitoring or calculating. Therefore, C and S should be quantified at first. C could be quantified according to National Forest Fire Danger Weather Rating Forestry Industry Standard (LY / T 1063—2008). Quantified values for Combustible (C) are explained as below.

1- The proportion of nonflammable tree species is less than or equals 55%

2- Each proportion of tree species for the nonflammable, the fire-prone, and the flammable respectively is less than 55%, or the proportion of flammable tree species is from 55% to75%.

3- The proportion of flammable tree species reaches 75% or above.

4- The proportion of fire-prone tree species is from 55% to75%

5- The proportion of fire-prone tree species reaches 75% or above.

Table 1. Indicator system for transmission line wildfires rating and forecasting.

The First-Level Indicator	The Second-Level Indicator	The Third-Level Indicator
Indicator for transmission line wildfires rating and forecasting (A)	Factors to possibly cause wildfires (B_1)	Combustible (C)
		Seasonal fire source (S)
		Rainfall (R)
		Maximum temperature (T)
		Minimum air relative humidity (H)
		Wind velocity (V)
	Factors to indicate the threatened degree of the power grid by wildfires (B_2)	Highest voltage grade (U)
		Power gird density (G)

Table 2. Relationships between the grade of wildfire danger and the evaluation indicators.

Transmission Line Wildfire Danger Grade	The Degree of Danger	C	S	R (mm)	T (°C)	H (%)	V (m/s)	U (kV)	G (km/km^2)
I	Safe	1	1	>10.0	<5.0	>75	<0.3	<35	<0.1
II	Lower	2	2	5~10.0	5.0~12.0	60~75	0.3~3.3	35~110	0.1~0.3
III	Medium	3	3	2.0~5.0	12.0~19.0	45~60	3.3~7.9	110~220	0.3~0.6
IV	High	4	4	0.3~2.0	19.0~25.1	30~45	7.9~20.7	220~500	0.6~1.0
V	Extremely high	5	5	<0.3	>25.1	<30	>20.7	>500	>1.0

Table 3. The Satisfied values and the disallowed values for each evaluation indicator.

Limit Value	C	S	R (mm)	T (°C)	H (%)	V (m/s)	U (kV)	G (km/km^2)
Satisfied value	1	1	10.0	5.0	75	0.3	35	0.1
Disallowed value	5	5	0.3	25.1	30	20.7	500	1.0

S could be quantified by statistically analyzing history data of wildfire occurrence and according to changes of season and features of human activities as below.

1- August, September

2- June, July

3- January, February, November, December

4- May, October, Ghost Festival, Autumn harvest

5- March, April, Qingming Festival, Spring Festival, Spring plough

With the above indicator system, the relationships between the grade of wildfire danger and assessment indicators are showed in Table **2**.

3.2. Satisfied Value and Disallowed Value of Each Assessment Indicator

The range of each evaluation indicator for each grade of wildfire danger is given in Table **3**. The standard index limit values in grade I (safe) are taken as satisfied values, and the ones in grade V (extreme) are taken as disallowed values.

3.3. Calculation of Single Efficacy Coefficient

In the above evaluation system of wildfire danger rating and forecasting of transmission lines, combustible (C), seasonal fire source(S), maximum temperature (T), wind velocity (V), grade of voltage (U), and power grid density (G) are maximum-type variables, and their single efficacy coefficients would be calculated with formula (1). Minimum air relative humidity (H) and rainfall (R) are minimum-type variables, and their single efficacy coefficients would be calculated according to formula (2).

3.4. Improve the Determination of Index Weight

Weight reflects the importance degree of each indicator to the overall assessment result. The vector for each indicator could be expressed as $W = (w_1, w_{2,} \cdots w_n)$, and the normalization condition should be meet, *i.e.* $\sum_{i=1}^{n} w_i = 1$.

To determine the importance degree of each factor to the overall objective, To determine the weight of each indicator to the overall objective, AHP (analytic hierarchy process) method was applied in this paper to build the comparison matrix $X=[x_{ij}]_{n\times n}$ [7, 8]. The comparison matrix is usually given by experts according to their actual experience. In comparison, 9-point scale method is applied as showed in Table **4** [9, 10].

Table 4. 9-Point scale method and its interpretation.

Criterion	The Scale Value of x_{ij}
i and j are the same important.	1
i is slightly more important than j.	3
i is obviously more important than j.	5
i is much more important than j.	7
i is extremely more important than j.	9

Experts valued the importance for each indicator of each level in indicator system of transmission line wildfire danger rating and forecasting by 9-point scale measurement based on their own experiences, and judgment matrixes of A, B1 and B2 are showed below.

$$A=\begin{bmatrix} 1 & 2/3 \\ 2/3 & 1 \end{bmatrix} \quad (6)$$

$$B_1=\begin{bmatrix} 1 & 1 & 1/4 & 1/2 & 1/3 & 1 \\ 1 & 1 & 1/4 & 1/2 & 1/3 & 1 \\ 4 & 4 & 1 & 2 & 4/3 & 4 \\ 2 & 2 & 1/2 & 1 & 2/3 & 1 \\ 3 & 3 & 3/4 & 3/2 & 1 & 1 \\ 1 & 1 & 1/4 & 1 & 1 & 1 \end{bmatrix} \quad (7)$$

$$B_2=\begin{bmatrix} 1 & 1/2 \\ 2 & 1 \end{bmatrix} \quad (8)$$

After consistency measurement of the above matrixes, local weights in each level were calculated as in Table **5**. Overall weights for each impact factor to overall objective have been worked out as showed in Table **6**.

3.5. Determination on Wildfire Danger Rating of Transmission Lines

After calculation of overall efficacy coefficient according to formula 5, wildfire danger rating of transmission lines could be worked out as showed in Table **7**.

Table 7. Transmission line wildfire danger rating and description.

Grade of Wildfire Danger	Overall Efficacy Coefficient	Description
I	≤60	Safe
II	60~70	Lower
III	70~80	Medium
IV	80~90	High
V	≥90	Extremely high

4. CASE STUDY

4.1. Profile of the Experimental Case

In this paper, an example in a northern province of China has been presented to test the validation of the above model. The history data on wildfire, meteorology and transmission line failures caused by wildfires in 2012 have been collected for statistical analysis in this case. The analysis result shows the consistency with the actual situation of wildfire occurrence in general, *i.e.* the occurrence of wildfires is well relative to the changes of seasons, meteorology and human activities. The distribution of wildfire occurrence from April in 2012 to May in 2014 is showed in Fig. (**1**).

Table 5. Local weighs and logic consistency measurement.

A	B1			B2			λ_{max}	CI	CR
	0.4000			0.6000			2	0	0
B1	C	S	R	T	H	V	λ_{max}	CI	CR
	0.0853	0.0853	0.3411	0.1509	0.2165	0.1210	6.1498	0.0300	0.0120
B2	U			G			λ_{max}	CI	CR
	0.3333			0.6667			2	0	0

Table 6. Overall weights of each impact factor to overall objective.

	C	S	R	T	H	V	U	G
W	0.0341	0.0341	0.1364	0.0603	0.0866	0.0484	0.2000	0.4000

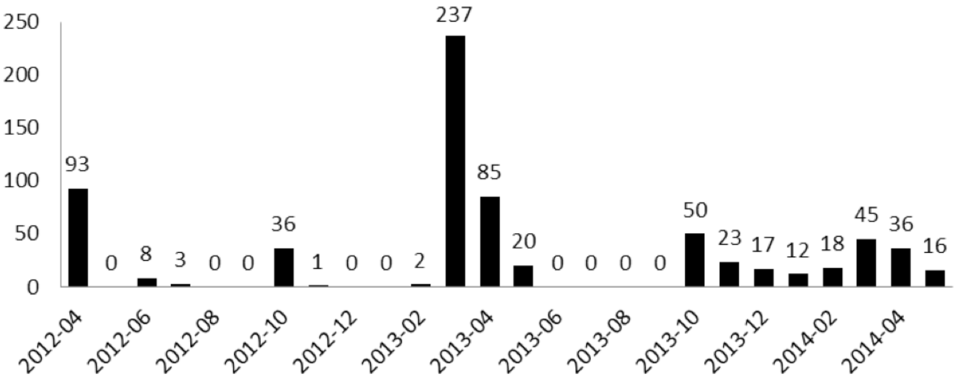

Fig. (1). Monthly distribution of wildfires from 2012 to 2014 in the study area.

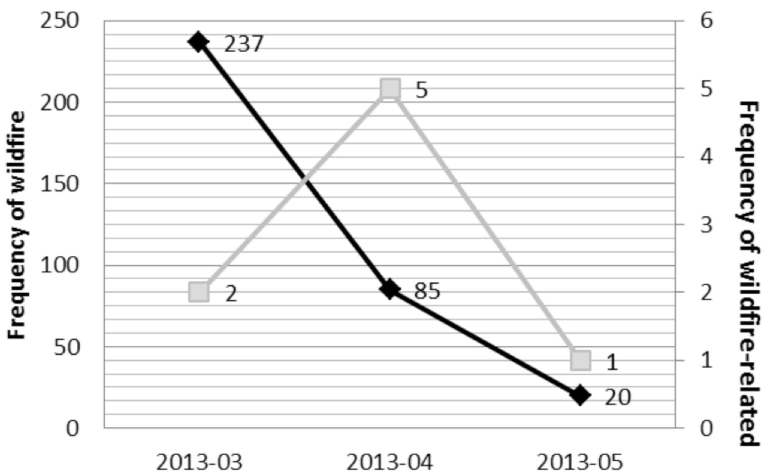

Fig. (2). Comparisons in frequency between wildfire and wildfire-caused power grid failure from March to May, 2013, in the study area.

The situation of wildfire occurrence was the most serious from March to May in 2013, and a comparison in frequency between the situation of wildfire occurrence and wildfire-relevant tripping failures on transmission lines at the voltage grade beyond 500kv has been made in Fig. (**2**), in which the gray fold line represents for the occurrence trend of wildfire-related power failures, and the black one for the occurrence trend of wildfires. The analysis result shows that wildfire-relevant failure on transmission lines is related to common wildfire occurrence but not necessarily. For instance, wildfires occurred more frequently in the March with 237 times than in the April with 87 times but transmission line wildfire-caused failures are less in the March than in the April, which reveals that more frequent wildfires don't necessarily cause more troubles to the power grid. In other word, under the condition of a high grade of wildfire danger rating, the risk of wildfire-caused failure on transmission lines is not necessarily high. A typical case is that there is no risk to power grid under an extremely high grade of wildfire danger rating where no transmission lines run across.

4.2. Forecasting on Wildfire Danger Rating Based on Efficacy Coefficient Method

According to the statistical data, 8 sets of typical data have been selected to forecast the wildfire danger rating using efficacy coefficient method. The result has been compared with the one got by the method of forest fire danger weather composite indicator (FFDWCI) in Table **8**.

In the above table, the grade of wildfire danger rating calculated by total efficacy coefficient method and the one by forest fire danger weather composite indicator method are different to some extent. The grades of wildfire danger rating got by the former method in set 1, set 6, and set 8 of data are lower but in set 2, set 3 and set 5 of date are higher than the ones got by the latter method, and the ones in set 4 and set 7 of data are consistent for two method. The above difference is mostly resulted from the difference on factors of U and G which are related to power grid itself. The value of those indicators are smaller in set 1, set 6, and set 8 of data, larger in set 2, set 3 and set 5 of data, and medium in set 4 and set 7 of data. To illustrate this difference intuitively, the forecasting results in Table **8** have been sorted in an ascending order to draw a radar map in Fig. (**3**).

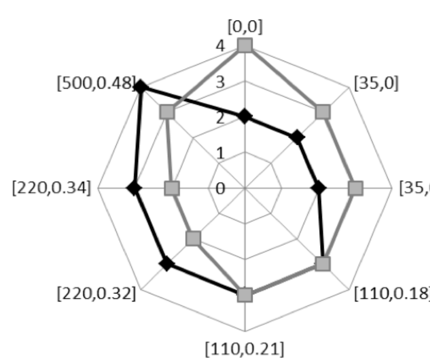

Fig. (3). Analysis on forecasting results for two methods in the study area.

Table 8. Transmission line wildfire forecasting results in the study area.

No.	Time of wildfire occurrence	Assessment indicators								Total Efficacy Coefficient Method		Forest Fire Danger Weather Composite Indicator Method	
		C	S	R (mm)	T (°C)	H (%)	V (m/s)	U (kV)	G (km/km^2)	Value	Grade	Value	Grade
1	2013.03.08	4	5	0	26	17	5.6	0	0	69.20	II	75	IV
2	2013.03.14	3	5	0	27	35	4.8	500	0.48	87.39	IV	66	III
3	2013.08.06	4	1	0.5	33	72	3.3	220	0.34	75.82	III	35	II
4	2013.10.16	4	4	0	17	38	1.2	110	0.18	73.30	III	58	III
5	2014.02.04	3	5	0.8	1	42	6.2	220	0.32	76.00	III	32	II
6	2014.03.09	4	4	0	13	38	10.5	35	0	68.50	II	63	III
7	2014.05.06	4	4	0	23	40	3.7	110	0.21	74.66	III	63	III
8	2014.05.24	4	4	0	28	66	5.8	35	0	67.39	II	53	III

In Fig. (**3**), the black curve represents for the result of efficacy coefficient method and the gray curve for the one of forest fire danger weather composite indicator method. The result shows that the grade of wildfire danger rating got by the former method is lower than the one by the latter method when the value of power grid factors is smaller, *i.e.*, the grade of voltage is lower than 110kv and G is less than 0.1, that the grade of wildfire danger rating got by the former method is identical to the one by the latter method when the value of power grid factors is medium, *i.e.*, the grade of voltage varies from 110kv to 220kv and G from 0.1 to 0.3, and that the grade of wildfire danger rating got by the former method is higher than the one by the latter method when the value of power grid factors is larger, *i.e.*, the grade of voltage is higher than 220kv and G is more than 0.3. In the last situation, the risk of transmission line failure caused by wildfire is highest. In fact, provincial power entrepreneurs always pay more attention to the transmission lines at the voltage grade of 110kv or beyond. Therefore, under the same environmental conditions, the risk of wildfire around the high-voltage-grade transmission lines should catch more attention from power entrepreneurs. The above case has proved that consistency exists between the quantitative grade of transmission line wildfire by efficacy coefficient method and the actual situation in practice, which shows the validation of this method. This method could support the prevention from transmission line wildfire.

5. CONCLUSION

1) In this paper, power grid factors were combined with meteorological factors and environmental factors for the first time to put forth a wildfire rating and forecasting indicator system for transmission lines exclusively, in which the grade of wildfire danger could be corrected by using the voltage grade and the power grid density. Besides, seasonal factors and wildfire-related traditional festivals have been taken into account while normalizing for the first time. A new idea for transmission line wildfire danger rating & forecasting has been explored in this paper.

2) In this paper, the feasibility and the application of transmission line wildfire rating &forecasting based on efficacy coefficient method have been discussed. Meanwhile, AHP has been used to calculate weights for each indicator. The feasibility and applicability have been finely verified in the section of case study.

3) Transmission line wildfire danger has been classified into 5 grades, which is similar to the classification of forest fire danger weather composite indicator method adopted by China Forestry Industry. I is the lowest grade and stands for “safe”; V is the highest and stands for “extremely dangerous”. By the verification in the case, the result shows that the higher the value of power grid factors, the higher the grade of transmission line wildfire danger. Besides, under the same environmental conditions, once the values of power grid factors exceed the limits, *i.e.*, voltage grade is higher than 220kv and the power grid density is larger than 0.3., the grade of transmission line wildfire danger will be higher than the one of forest fire danger got by forest fire danger composite indicator method, and vice versa, which is identical to the actual situation in the power grid operation.

4) To conclude, when the transmission line wildfire danger got by the efficacy coefficient method reaches the grade of III or beyond, the leader or manager in power grid entrepreneurs should pay more attention to the corridors of those lines. While it reaches the grade of V, operators and managers should take measures to mainly stop power failures caused by wildfires.

5) It is an initial attempt that the transmission line wildfire danger rating and forecasting based on efficacy coefficient method has been studied in this paper. Therefore, further explores and improvements are needed, for example, how could the reliability and accuracy be improved by correcting each indicator; how could the power grid factors be further refined and enhanced for being more reasonable and more practical. Besides, since a case has been studied only in an area of a northern province in China, this method could be used in other regions only after the limits of indicators are corrected to be identical to the actual situation.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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