Proceedings of ES2008
Energy Sustainability 2008
August 10-14, 2008, Jacksonville, Florida USA

ES2008-54087

APPLICATION OF ENTROPY METHOD IN FUZZY SYNTHETIC EVALUATION FOR MICRO-TURBINE PERFORMANCE

Guohua Shi, Youyin Jing, Songling Wang, Yuefen Gao

Education Ministry Key Laboratory on Condition Monitoring and Control of Power Plant Equipment, North China Electric Power University, Baoding, CO 071003, China

ABSTRACT

Distributed generation (DG) is becoming the indispensable supplement to the centralized generation. Micro-turbine is paid more and more attention in scientific research and commercial application due to its unique advantages and gradually becomes the core of distributed generation. It is essential to make a synthetic and scientific evaluation on the performance of micro-turbine in order to promote the progress of the distributed generation technology using micro-turbine. This article gives the synthetic performance evaluation of micro-turbine. Some performance characters (rated capacity, generating efficiency, rotation speed, pressure ratio, fuel consumption, multi-fuel, intake temperature, exhaust temperature, NO_x emission level, noises and life time) were chosen as evaluating indicators and some common micro-turbines were taken as evaluating objects in this paper. Considering the difficulty of fuzzy synthetic evaluation method in calculation of the multiple factors and the ignorance of the relationship among evaluating objects, a new weight evaluation process using entropy method was introduced. The entropy method is an objective way for weight determination. The improved method for weight determination of the evaluating indicators was applied in performance assessment of the micro-turbines. The evaluation result of the example showed that this method was favorable for fuzzy synthetic evaluation when there was more than one evaluating objects and the entropy method for determination of weight was a very effective method for evaluating indicators. The method predigested the fuzzy synthetic evaluation process greatly and the evaluation results are more reasonable.

NOMENCLATURE

f_{ij}	relative normalized value of the *j*th evaluating object on the *i*th indicator
H_i	entropy of *i*th evaluating indicator
k	coefficient, k=1/ln$n$
L_2	evaluation vector
m	number of evaluating indicators
n	number of evaluating objects
r_{ij}	normalized value of the *j*th evaluating object on the *i*th indicator
R	normalized evaluating matrix of m×n
w_i	entropy weight of *i*th evaluating indicator
W	weight vector of evaluation indicators
x_{ij}	original value of the *j*th evaluating object on the *i*th indicator
X	original evaluating matrix of m×n
Subscript	
i	*i*th evaluating indicator
j	*j*th evaluating object
m	*m*th evaluating indicator
n	*n*th evaluating object

INTRODUCTION

Conventionally, power plants have generated electricity centrally and distributed it to electricity users through the expensive transmission and distribution networks. A new trend is the development of distributed generation (DG) as the supplement to the centralized generation to provide better energy quality and increase the power distribution reliability. DG can provide distinct technical and economic benefits to the electricity and users that are not available under the centralized generation system.

Distributed generation mainly depends on the installation and operation of a portfolio of small size, compact and clean electric power generating units at, or near to, the energy consumer to provide the electric power needed (sometimes also provide heating energy and cooling energy) [1].

There are different types of DG from the constructional and technological points of view. Three DG technologies are popular (internal combustion engines, micro-turbines, and fuel cells).

Distributed generation technologies with micro-turbine are of increasing interest in the energy market. Micro-turbines can operate using natural gas, propane, or diesel oil. They are compact in size and light in weight, so they can be installed even if there are space limitations. Also they have lower emissions and are very efficient. In addition, they can be operated easily, have good load tracking characteristics, and require less maintenance. Compared with other DG technologies, they consume lower auxiliary electricity and have lower capital costs. Because of these advantages, micro-turbines are paid more and more attention in scientific research and commercial application [2, 3].

To promote the progress of the distributed generation technology using micro-turbine, it is important to manufacture many micro-turbines with good performance. However, there is no a standard to judge whether the performance of a micro-turbine is good or not because there are many factors influencing it. This paper analyzed performance factors of micro-turbine and chose some as evaluating indicators in fuzzy synthetic evaluation for micro-turbine performance. Then the entropy method was used to determine the weight of these indicators and applied to evaluate some common micro-turbines performance. The evaluation result can provide guides to design of micro-turbines.

EVALUATION METHOD

The definition of entropy firstly appeared in thermodynamics and it was used for describing the non-reversibility of one process. Shannon introduced it into the information theory in 1948. Now it has been widely used in engineering, economy, finance, etc. [4]. Information entropy can measure the disorder degree of a system and the amount of useful information according to the data provided. On the same evaluation indicator, if the difference of the value among the evaluating objects is higher, the entropy is smaller. This indicates that the indicator provides more useful information and its weight should be corresponding higher. On the contrary, the entropy is higher and its weight should be smaller when the difference is smaller [5]. It is obvious that the entropy method is an objective method for weight determination. It can reflect the relationship among all evaluating objects.

Formation of Original Evaluating Matrix

Suppose there are evaluating indicators accounted m and evaluating objects accounted n. The ith (i=1,2,…,m) indicator's value of the jth (j=1,2,…,n) evaluating object is x_{ij}. Then the original evaluating matrix, $X=(x_{ij})_{\mathrm{m}\times\mathrm{n}}$, can be formed.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

For the ith (i=1,2,…,m) indicator, if the difference of x_{ij} is large, it means the indicator provides more useful information and is more important in the evaluation.

Normalization of the Original Evaluating Matrix

Different evaluating indicators usually have different dimensions, so it is impossible and meaningless to compare them directly. It is necessary to convert each value of X to dimensionless value in order to do the evaluation. Among these indicators, to which the bigger the better

$$r_{ij} = \frac{x_{ij} - \min_{j=1}^{n}\left(x_{ij}\right)}{\max_{j=1}^{n}\left(x_{ij}\right) - \min_{j=1}^{n}\left(x_{ij}\right)} \tag{2}$$

to which the smaller the better, there are

$$r_{ij} = \frac{\max_{j=1}^{n}\left(x_{ij}\right) - x_{ij}}{\max_{j=1}^{n}\left(x_{ij}\right) - \min_{j=1}^{n}\left(x_{ij}\right)} \tag{3}$$

where r_{ij} is the value of the jth evaluating object on the ith indicator.

After the normalization, it is obvious that r_{ij} is dimensionless and $r_{ij}\in[0,1]$. Thus, the normalization of X produces the matrix (Eq.(4)):

$$R = \left(r_{ij}\right)_{\mathrm{m}\times\mathrm{n}} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{4}$$

Definition of the Entropy

The entropy of the ith (i=1,2,…,m) evaluating indicator is defined as Eq.(5).

$$H_i = -k\sum_{j=1}^{n} f_{ij} \ln f_{ij} \tag{5}$$

$$f_{ij} = r_{ij} \Big/ \sum_{j=1}^{n} r_{ij} \tag{6}$$

$$k = 1/\ln n \tag{7}$$

where H_i is the entropy of the ith indicator. Suppose $H_i = -k\sum_{j=1}^{n} f_{ij} \ln f_{ij} = 0$, when f_{ij}=0.

Definition of the Entropy Weight

The entropy weight of the ith indicator is defined as:

$$w_i = \frac{1-H_i}{m-\sum_{i=1}^{m} H_i} \tag{8}$$

in which $w_i \in [0,1]$ and $\sum_{i=1}^{m} w_i = 1$.

Then the weight vector of evaluation indicators can be generated as:

$$W = \left(w_1, w_2, \cdots, w_m\right) \tag{9}$$

The weight value of an indicator shows the effect in the evaluation process. The higher value of the indicator, the more important it is.

Definition of the Evaluation Vector

Based on the conception of L-valued Zadeh functions, L_2 is used as the vector for evaluating all evaluation objects. L_2 is defined as Eq.(10) [6].

$$L_2\left(w, j\right) = \sqrt{\sum_{i=1}^{m} w_i^2 \left(1-r_{ij}\right)^2},\ j = 1, 2, \cdots, n \tag{10}$$

If the L_2 value of an evaluation object is smaller among all objects, the performance of the object is more excellent. So the performance ranking of all objects can be done depending on their L_2 values.

EVALUATION OF MICRO-TURBINE PER-FORMANCE

Evaluating Indicators

The selection of evaluating indicators is the first and important step during the process of fuzzy synthetic evaluation. All indicators should be selected according to the characteristics of evaluating objects, and be independent and comparable. Otherwise, it would affect the evaluation results negatively.

DGs with micro-turbine have been developed only since the beginning of the 1990s. The performance of micro-turbines should be improved continuously. At present, existing micro-turbine sizes mainly vary from 25kW to 100kW. Some undermentioned targets must be achieved in USA in the near future [7, 8].

1) The generating efficiency of micro-turbines should exceed 40%.

2) The emission of NO_x should be less than 7 ppm for the full micro-turbine load, if micro-turbines use natural gas as fuel.

3) The maintenance period should be longer than 11,000 hours and the service life should exceed 45,000 hours.

4) Micro-turbines should be able to use various fuels, such as diesel oil, natural gas, ethanol, landfill gas and biofuels.

These characteristics are expected to improve the micro-turbine performance. In addition, other characteristics also influence the performance, such as fuel consumption, exhaust temperature etc. Considering the economic performance, applicability, reduced emissions, and maintainability synthetically, the selection of rated capacity, generating efficiency, rotation speed, pressure ratio, fuel consumption, multi-fuel, intake temperature, exhaust temperature, NO_x emission level, noises, and life time as evaluating indicators is performed. These indicators are noted as I= [I_1,I_2,…,I_{11}]. If a micro-turbine combusts natural gas as well as diesel oil, I_6 is stipulated to equal to 1. If it only combusts natural gas or diesel oil, I_6 equals to 0. It is obvious that rated capacity, generating efficiency, rotation speed, pressure ratio, multi-fuel, intake temperature, and life time belong to the indicators “the bigger the better”, and others belong to the indicators “the smaller the better”.

Evaluating Objects

In the U.S., Japan and some European countries, the government and non-government institutions and scholars have been paying more attention to the micro-turbine technology and are focusing now on the characteristics of micro-turbines rather than on the overall number of installations. Some advanced micro-turbines have been developed and manufactured in these countries and commercially available in the international market [9]. For example, there are 30kW and 75kW capacity cogeneration units that can either be connected in parallel to the grid or act as a standalone unit to provide lower cost electricity and reliable backup.

Six common micro-turbines are selected as the evaluating objects and noted as EO=[EO_1,EO_2,…,EO_7] in the paper. Table 1 summarizes the specifications of these typical micro-turbines.

Original Evaluating Matrix

Using the data from the Table 1, the original evaluating matrix X can be produced.

Table 1 Parameters of the evaluating objects

Parameter	EO_1	EO_2	EO_3	EO_4	EO_5	EO_6	EO_7
I_1 (rated capacity) (kW)	60	75	80	80	2.6	70	75
I_2 (generating efficiency) (%)	25	28.5	27	27.5	9	33	28.5
I_3 (rotation speed) (r/min^{-1})	96000	65000	99750	110000	100000	60000	65000
I_4 (pressure ratio)	3.2	3.7	4.3	4.0	2.8	3.3	3.7
I_5 (fuel consumption) (m^3/h)	9.3	22.2	17.3	15.6	1.4	18.4	22.2
I_6 (multi-fuel)	1	1	1	1	0	1	1
I_7 (intake temperature) (℃)	840	920	680	920	850	870	930
I_8 (exhaust temperature) (℃)	270	250	300	280	250	200	250
I_9 (NO_x emission level) (ppm)	9	25	9	25	25	9	17
I_{10} (noises) (dB)	65	65	75	65	55	65	65
I_{11} (life time) (h)	40000	40000	40000	54000	40000	80000	40000

$$X=\begin{bmatrix} 60 & 75 & 80 & 80 & 2.6 & 70 & 75 \\ 25 & 28.5 & 27 & 27.5 & 9 & 33 & 28.5 \\ 96000 & 65000 & 99750 & 110000 & 100000 & 60000 & 65000 \\ 3.2 & 3.7 & 4.3 & 4.0 & 2.8 & 3.3 & 3.7 \\ 9.3 & 22.2 & 17.3 & 15.6 & 1.4 & 18.4 & 22.2 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 840 & 920 & 680 & 920 & 850 & 870 & 930 \\ 270 & 250 & 300 & 280 & 250 & 200 & 250 \\ 9 & 25 & 9 & 25 & 25 & 9 & 17 \\ 65 & 65 & 75 & 65 & 55 & 65 & 65 \\ 40000 & 40000 & 40000 & 54000 & 40000 & 80000 & 40000 \end{bmatrix} \quad (11)$$

Normalization Evaluating Matrix

Using Eq.(2) and Eq.(3), X can be normalized as:

$$R=\begin{bmatrix} 0.742 & 0.935 & 1.000 & 1.000 & 0.000 & 0.871 & 0.935 \\ 0.667 & 0.813 & 0.750 & 0.771 & 0.000 & 1.000 & 0.813 \\ 0.720 & 0.100 & 0.795 & 1.000 & 0.800 & 0.000 & 0.100 \\ 0.267 & 0.600 & 1.000 & 0.800 & 0.000 & 0.333 & 0.600 \\ 0.620 & 0.000 & 0.236 & 0.317 & 1.000 & 0.183 & 0.000 \\ 1.000 & 1.000 & 1.000 & 1.000 & 0.000 & 1.000 & 1.000 \\ 0.640 & 0.960 & 0.000 & 0.960 & 0.680 & 0.760 & 1.000 \\ 0.300 & 0.500 & 0.000 & 0.200 & 0.500 & 1.000 & 0.500 \\ 1.000 & 0.000 & 1.000 & 0.000 & 0.000 & 1.000 & 0.500 \\ 0.500 & 0.500 & 0.000 & 0.500 & 1.000 & 0.500 & 0.500 \\ 0.000 & 0.000 & 0.000 & 0.350 & 0.000 & 1.000 & 0.000 \end{bmatrix} \quad (12)$$

The Entropy and the Entropy Weight

For all indicators, the entropies and the entropy weights can be calculated from Eq.(5)-Eq.(8). The results are listed in Table 2.

The sum of entropy weights of all indicators equals to 1. Table 2 shows that the weight is bigger if the entropy of one indicator is smaller. Because the differences between some indicator, for example, rated capacity and generating efficiency, are small, some indicators (fuel consumption, life time and NO_x emission), especially life time, play more important roles in the evaluation process and have more influence on the evaluation result. Thus, manufacturers can make their products more excellent and more competitive in market by improving one or several indicators. If one indicator entropy weight is bigger, it only means that the indicator is more important in the evaluation for the specific evaluating objects and the certain indicator combinations.

Table 2 Entropies and entropy weights of the indicators

Evaluation indicator	Entropy (H)	Entropy Weight (w)
I_1	0.918	0.038
I_2	0.917	0.038
I_3	0.801	0.092
I_4	0.874	0.058
I_5	0.727	0.126
I_6	0.921	0.037
I_7	0.913	0.041
I_8	0.860	0.065
I_9	0.718	0.131
I_{10}	0.898	0.047
I_{11}	0.294	0.327

Evaluation Vector and Evaluation Result

The evaluation vector can be calculated according to Eq.(10).

$$L_2=\begin{bmatrix}0.339 & 0.386 & 0.353 & 0.271 & 0.365 & 0.146 & 0.369\end{bmatrix} \quad (13)$$

Based on the definition of L_2 and Eq.(13), the performance ranking of the seven micro-turbines is derived as shown in Table 3.

Table 3 Performance ranking of the evaluating objects

Objects	EO_1	EO_2	EO_3	EO_4	EO_5	EO_6	EO_7
Ranking	3	7	4	2	5	1	6

By the entropy method for determination of evaluating indicator weight, the evaluation result implies that the synthetic performance of 70-kW micro-turbine "EO_6" is most excellent among the seven micro-turbines, while the performance of 75-

kW micro-turbine "EO_2" is worst. It is more scientific and reasonable than performance assessment for micro-turbines only depending on some indicator.

CONCLUSIONS

This evaluation takes into consideration the fuzzy characteristics of micro-turbine performance and establishes the major influencing factors. The entropy method is used for determination of indicator weight of each performance parameter. The evaluation is simple and not time-consuming, and one calculation is performed to get a set of weights for all evaluating objects. The entropy method considers adequately the information on values among all evaluation objects. It compensates for the negative effect from some abnormal values and makes the evaluation result more reasonable and objective. The evaluation result of the presented test case example indicates that the method is effective for evaluation of micro-turbine performance, especially in the case that lacks of reasonable subjective indicator weights from experts and only has data of all indicators. Thus, this method is an effective multifactor comprehensive evaluation method for micro-turbine performance.

The evaluation results using this method can compare micro-turbine performance, and provide guidance for manufactures how to improve design of products and for users how to make proper selection of equipment.

ACKNOWLEDGEMENTS

The authors are grateful to the YOUTH TEACHER FUND OF NORTH CHINA ELECTRIC POWER UNIVERSITY and the EDUCATION MINISTRY KEY LABORATORY ON CONDITION MONITORING AND CONTROL OF POWER PLANT EQUIPMENT OF CHINA for the support.

REFERENCES

[1] El-Khattam, W. and Salama, M.M.A., 2004, "Distributed generation technologies, definitions and benefits", Electric Power Systems Research, Vol.71, pp.119-128.
[2] Weng, Y.W., Weng, S.L. and Su, M., 2003, "Distributed power system based on micro gas turbine", Electric Power, Vol.36, pp.1-4.
[3] Jin, Z.P., 2005, "Application of gray related analysis method in performance appraisal of microturbine", Gas Turbine Technology, Vol.18, pp.49-51.
[4] Zou, Z.H., Sun, J.N. and Ren, Z.P., 2006, "Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment", Journal of Environment Sciences, Vol.18, pp.1020-1023.
[5] Qiu, W.H., 2002, "Management decision and applied entropy, China Machine Press", pp.193-196.
[6] Zadeh, L.A., 1996, "Fuzzy sets, fuzzy logic and fuzzy systems", World Scientific Publishing Co., Inc., pp.775-782.
[7] Advanced microturbine system-program plan for fiscal years from 2000 through 2006, U.S. Doe. Office of Power Technologies, pp.1-15.
[8] Weng, Y.W. and Su, M., 2003, "Specific features of advanced micro gas turbines and their application prospects", Journal of Engineering for Thermal Energy & Power, Vol.18, pp.111-115.
[9] Onovwiona, H.I. and Ugursal, V.I., 2006, "Residential cogeneration systems: review of the current technology", Renewable and Sustainable Energy Reviews, Vol.10, pp.389-431.

