Electrical Power and Energy Systems 45 (2013) 468–476

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

An improved fuzzy synthetic condition assessment of a wind turbine generator system

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ARTICLE INFO

Article history:
Received 15 December 2011
Received in revised form 12 September 2012
Accepted 26 September 2012
Available online 7 November 2012

Keywords:
Wind turbine generator system
Condition assessment
Fuzzy synthetic
Real-time monitoring

ABSTRACT

This paper presents an improved fuzzy synthetic model that is based on a real-time condition assessment method of a grid-connected wind turbine generator system (WTGS) to improve the operational reliability and optimize the maintenance strategy. First, a condition assessment framework is proposed by analyzing the monitored physical quantities of an actual WTGS with an electrically excited synchronous generator (EESG) and a full-scale converter. To examine the variable speed operational performances, the dynamic limits and the deterioration degree functions of the characteristic variables are determined by analyzing the monitoring data of the WTGS. An improved fuzzy synthetic condition assessment method is then proposed that utilizes the concepts of deterioration degree, dynamic limited values and variable weight calculations of the assessment indices. Finally, by using on-line monitoring data of an actual 850 kW WTGS, real-time condition assessments are performed that utilize the proposed fuzzy synthetic method; the model's effectiveness is also compared to a traditional fuzzy assessment method in which constant limited values and constant weights are adopted. The results show that the condition assessment that utilizes the improved method can predict the change of operating conditions and has a better coherence with real operating conditions than that of a traditional fuzzy assessment method.

1. Introduction

Renewable energy sources, especially wind energy, are considered important generation alternatives in electric power systems due to their non-exhaustive nature and benign environmental effects [1,2]. Currently, more large-scale wind farms are being installed and planned. With the advanced development of wind power generation technologies, offshore wind power generation has become more attractive than onshore wind power generation [3,4]. Consequently, real-time reliability assessment and condition monitoring have become increasingly important due to extreme offshore environments and high maintenance costs [5]. Because of the variable speed constant frequency (VSCF) operational performance of a WTGS, their on-line monitoring characteristic variables have a wider operational range, subjecting them to higher failure rates than traditional power generation systems [6–8]. To assure a satisfactory level of real-time operational reliability and to suitably arrange the optimal maintenance strategies during the lifetime of a WTGS, it is necessary to effectively assess the real-time operational condition.

Several condition monitoring techniques have been applied to WTGS, but these techniques and assessments are typically focused on a single component of a WTGS, such as the blades [9], gearbox [10], and electrical systems [11,12], making it impossible to comprehensively examine the overall condition of the wind turbine system. Furthermore, these mentioned condition-monitoring techniques typically require additional sensors or equipments, directly increasing the costs of a WTGS [13,14]. A system-level real-time condition assessment, based on on-line monitoring data from an existing control system of a WTGS or supervisory control and data acquisition (SCADA) system of a large-scale wind farm that can evaluate a WTGS through an advanced assessment method is becoming more attractive [9,15–17]. A data-driven approach for monitoring blade pitch faults in wind turbines was presented in [9], but the selection of the characteristic variables did not consider the wind turbine control performance and obscured the reasoning process. Furthermore, a data-driven approach usually requires numerous training samples that can hinder an on-line condition assessment because of complex calculations. A fuzzy comprehensive evaluation method may be a suitable approach to assess the on-line condition of a WTGS [18] because it can utilize the concepts of fuzzy mathematics and fuzzy relation composition to more easily quantify factors with ambiguous boundaries [19]. However, the operational characteristics of a WTGS are different from

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http://dx.doi.org/10.1016/j.ijepes.2012.09.014

traditional electrical equipment due to wind speed variation, and the impact levels of different components on the health condition of a WTGS are also heavily dependent on the operational point. Thus, the traditional fuzzy assessment method must be improved to effectively assess the WTGS real-time conditions, by further investigating the important considerations including the dynamic limits of the characteristic variables, the different variable weight designs and the indices classifications.

To provide an example of a variable speed constant frequency WTGS with an electrically excited synchronous generator (EESG), this paper presents an improved fuzzy synthetic model based on a real-time condition assessment method. First, the condition assessment framework is proposed by analyzing the monitoring physical quantities of the presented WTGS system. The dynamic limits and the deterioration degree functions of the assessment of the characteristic variables are determined by analyzing the monitoring data of the WTGS. The improved fuzzy synthetic condition assessment model is then proposed by utilizing the concepts of deterioration degree, dynamic limited values, and variable weight calculations of the assessment indices. Finally, by using on-line monitoring data of an actual 850 kW WTGS, real-time condition assessments are performed that use the proposed fuzzy synthetic model; the effectiveness is also compared to a traditional fuzzy assessment method in which constant limited values and constant weights are adopted.

This paper proposes a condition assessment structure and an improved fuzzy synthetic assessment method for a WTGS. In Section 2, the condition assessment framework, the dynamic limits and the deterioration degree functions are presented, respectively. In Section 3, the improved fuzzy synthetic condition assessment model is described, including fuzzification, variable weight calculation and defuzzification. In Section 4, the accuracy and validity of the improved fuzzy synthetic assessment method are verified by using the on-line monitoring data of an actual WTGS; the results are then compared to a traditional fuzzy assessment method.

2. Design of condition assessment framework and characteristic indices

2.1. Condition assessment framework

One of the most important components of a WTGS is the control system; on-line operating information can be collected from the control system or SCADA system of a large-scale wind farm. This information can effectively reflect the real-time condition of a WTGS. This paper examines an example of a WTGS with a full rated converter (AC/DC/AC) and an electrically excited synchronous generator (EESG). Fig. 1 illustrates the configuration of this type of WTGS. The amplitude and frequency of the voltage can be fully regulated by the power converter at the generator side so that the generator speed can be fully controlled over a wide range.

Based on the frequently monitored physical quantities of the real control system of this WTGS, a framework of wind turbine condition assessment is proposed as shown in Fig. 2.

As shown in Fig. 2, the framework includes a destination layer index, project layer indices, sub-project layer indices and bottom layer indices. The project layer indices comprise two state indices, including unit performances index R_1 and extraneous factors index R_2, which can be further classified into other state indices in the sub-project layer indices and the bottom layer indices. For example, the unit performance index R_1 in the project layer indices can be classified into the indices of gearbox R_{11}, generator R_{12}, control cabinet R_{13} and nacelle R_{14} so that the unit performance index R_1 can be expressed by $R_1 = \{R_{11}, R_{12}, R_{13}, R_{14}\}$, while the gearbox index R_{11} can also be expressed by $R_{11} = \{R_{111}, R_{112}, R_{113}, R_{114}\}$. In Fig. 2, the nacelle position index R_{141} is usually expressed as an angle degree index, denoting the nacelle position of the round tower with the wind direction variation. If this position is beyond a certain limit, a cable twist fault may occur.

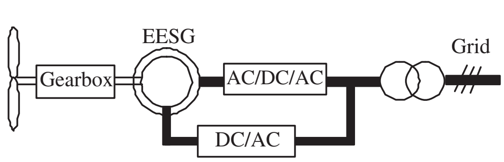

Fig. 1. Schematic of a variable-speed EESG wind turbine system.

2.2. Limited ranges of the characteristic variables

In a traditional fuzzy assessment model, fixed limited values are typically used to determine the ranges of characteristic variables. However, it may be unreasonable to set fixed limits for all the characteristic variables of a WTGS because of the wide variable speed operation ranges. Because of the VSCF operational performance of a WTGS, two types of indices can be classified in the indices layer based on the framework of the wind turbine real-time assessment system. The first type is focused on temperature variables, including the temperature of the gearbox bearing R_{111}, the gearbox oil cooled index R_{112}, and the generator bearing index R_{121}, which can be expressed through dynamic variable limits with fitting functions. The second type includes the speed of generator index R_{124}, the nacelle position index R_{141}, the vibration acceleration of nacelle index R_{142}, and the wind speed index R_{211}, which can be expressed through fixed limits.

The first type of indices was analyzed using the Bin method [20]. In this paper, the range of wind speed was divided into 200 bins ranging from 0 to 22 m/s, and all temperature values for each bin were averaged in the normal operational data. The function of all the presented temperature variables with the change of wind speed can be obtained by using the curve fitting method. As an example, Fig. 3 shows the relationship of the gear box bearing temperature index R_{111} and the wind speed for this WTGS.

Fig. 3 shows that if the wind speed is less than 3 m/s, the gear box bearing temperature remains effectively constant. At a wind speed of 3–18 m/s, the temperature increases proportionally with the increased wind speed. However, at wind speeds above 18 m/s, the temperature again remains nearly constant. Therefore, the fitting function could be derived as

$$x'_{R_{111}}(w) = \begin{cases} 45 & w < 3 \\ 0.0091w^3 + 0.3073w^2 & 3 \leqslant w \leqslant 18 \\ -1.4412w + 46.896 & \\ 68.5 & w > 18 \end{cases} \tag{1}$$

where w is wind speed and $x'_{R_{111}}(w)$ is the calculated temperature of the gear box bearing.

Based on the practical monitoring data of the WTGS, Table 1 shows the fitting functions of the first type assessment indices derived from the Bin method.

In order to use the above fitting function to express the dynamic performance of the WTGS, a degree of deviation $\Delta x_{R_{ijk}}$ can be used as

$$\Delta x_{R_{ijk}} = |x_{R_{ijk}} - x'_{R_{ijk}}| \tag{2}$$

where $x_{R_{ijk}}$ denotes the monitoring temperature and $x'_{R_{ijk}}$ denotes the calculated value with the fitting function.

Table 2 presents the fixed limits of the variables for the second type of indices, which can be used to assess conditions by judging whether the characteristic variables are beyond the fixed ranges.

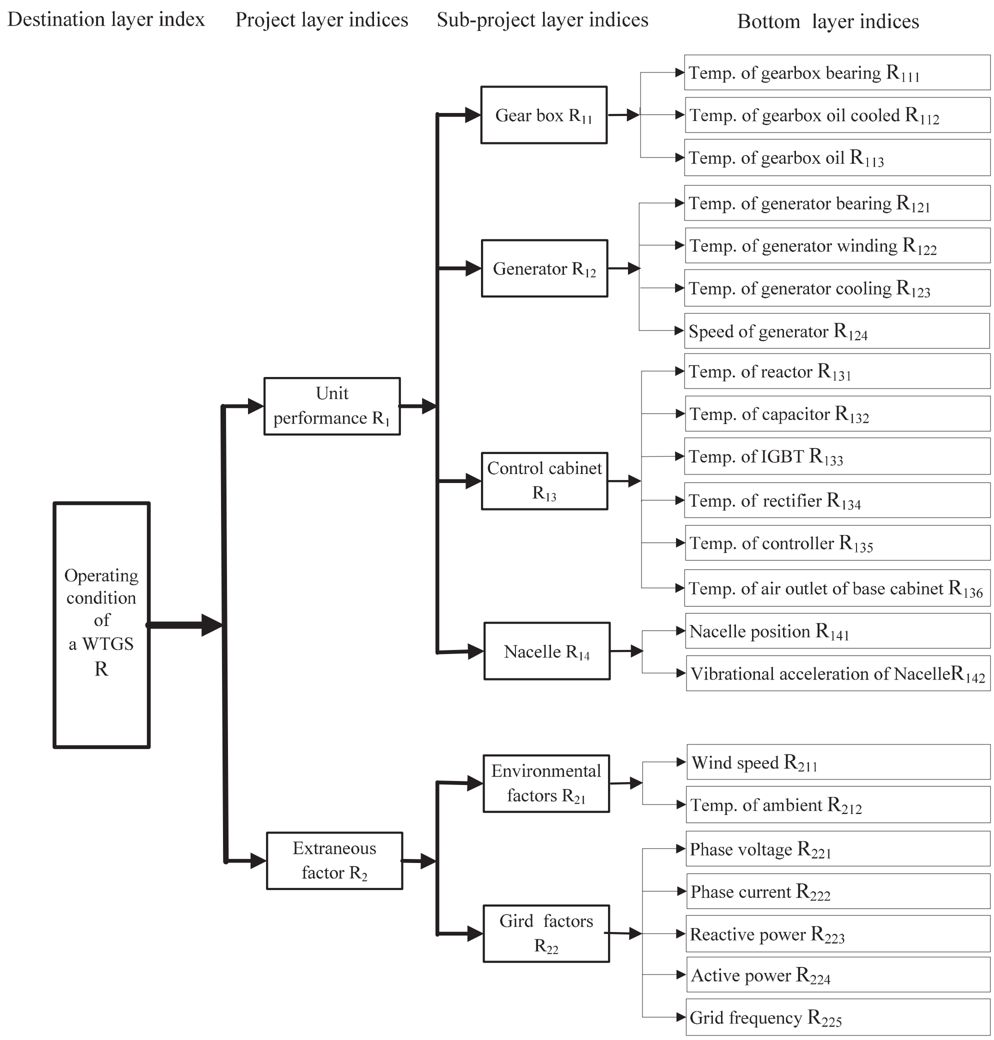

Fig. 2. Framework of wind turbine real-time condition assessment system.

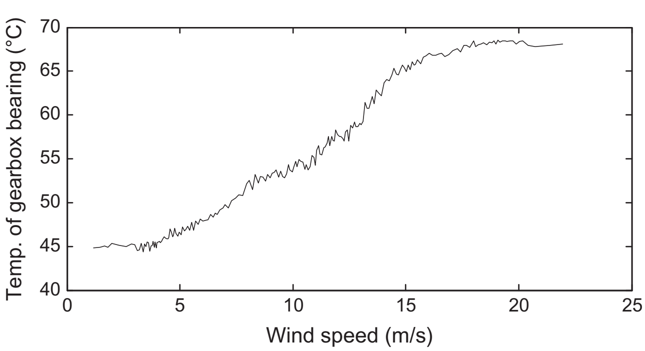

Fig. 3. Fitting function curve of temperature of gearbox bearing with the wind speed.

2.3. Deterioration degree of assessment indices

To evaluate the level of deterioration between the normal condition and the fault condition, the concept of deterioration degree is introduced in this paper. The deterioration degree is set in the range [0,1], the smaller the value the better condition of the WTGS [19]. The deterioration degree of the first type of indicators can be calculated as

$$g(\Delta x) = \begin{cases} 0, & \Delta x < \alpha \\ \frac{\Delta x - \alpha}{\beta - \alpha}, & \alpha \leqslant \Delta x \leqslant \beta \\ 1, & \Delta x > \beta \end{cases} \tag{3}$$

where g is the degree of deterioration, and α and β are the lower and upper limit values, respectively.

The deterioration degree of the second type of indicators can be defined as

$$g(x) = \begin{cases} 1, & x < \alpha_1 \\ \frac{x - \alpha_1}{\alpha_2 - \alpha_1}, & \alpha_1 \leqslant x < \alpha_2 \\ 0, & x = \alpha_2 \\ \frac{\alpha_3 - x}{\alpha_3 - \alpha_2}, & \alpha_2 < x \leqslant \alpha_3 \\ 1, & x > \alpha_3 \end{cases} \tag{4}$$

where α_1 and α_3 are the lower and upper limits, respectively, α_2 is the allowable value, and x is the monitoring index value.

3. Modeling of improved fuzzy synthetic condition assessment

The fuzzy synthetic assessment method is a comprehensive evaluation method based on fuzzy mathematics; the method converts qualitative evaluation into quantitative evaluation according to the membership degree theory of fuzzy mathematics. A general fuzzy synthetic assessment method is shown in Fig. 4, which

Table 1
Fitting functions of the first type indicators.

No.	Temp. type	The derived fitting function
1	Temp. of gearbox bearing	$x'_{R_{111}}(w)=\begin{cases}45 & w\leqslant 3\\ 0.0091w^3+0.3073w^2 -1.4412w+46.896 & 3<w\leqslant 18\\ 68.5 & w>18\end{cases}$
2	Temp. of gearbox oil cooled	$x'_{R_{112}}(w)=\begin{cases}45.48 & w\leqslant 3\\ 0.056w^2+0.2202w+43.984 & 3<w\leqslant 8.34\\ -1.1272w+59.261 & 8.34<w\leqslant 11.06\\ -0.1712w^2+6.8436w-8.952 & 11.06<w\leqslant 19.74\\ 59.56 & w>19.74\end{cases}$
3	Temp. of gearbox oil	$x'_{R_{113}}(w)=\begin{cases}46.08 & w\leqslant 3\\ -0.0102w^3+0.3525w^2-1.8662w+48.828 & 3<w\leqslant 18.57\\ 70 & w>18.57\end{cases}$
4	Temp. of generator bearing	$x'_{R_{121}}(w)=\begin{cases}38 & w\leqslant 3\\ 0.1226w^2-0.1741w+29.012+10 & 3<w\leqslant 15.53\\ 65.456 & w>15.53\end{cases}$
5	Temp. of generator winding	$x'_{R_{122}}(w)=\begin{cases}50.18 & w\leqslant 3\\ -0.0123w^3+0.5923w^2-3.5473w+57.139 & 3<w\leqslant 15.18\\ 93.48 & w>15.18\end{cases}$
6	Temp. of generator cooling	$x'_{R_{123}}(w)=\begin{cases}35.82 & w\leqslant 8.56\\ 0.2273w^2-3.2122w+46.692 & 8.56<w\leqslant 14.85\\ 49.14 & w>14.85\end{cases}$
7	Temp. of reactor	$x'_{R_{131}}(w)=\begin{cases}49.60 & w\leqslant 3\\ 4.5191w+34.79 & 3<w\leqslant 15.00\\ 103.56 & w>15.00\end{cases}$
8	Temp. of capacitor	$x'_{R_{132}}(w)=\begin{cases}26.09 & w\leqslant 6.468\\ 5.1037w-7.108 & 6.468<w\leqslant 15.00\\ 68.66 & w>15.00\end{cases}$
9	Temp. of IGBT R133	$x'_{R_{133}}(w)=\begin{cases}33.23 & w\leqslant 3\\ 0.3809w^2-3.0539w+39.373 & 3<w\leqslant 14.48\\ 73.67 & w>14.48\end{cases}$
10	Temp. of rectifier	$x'_{R_{134}}(w)=\begin{cases}32.96 & w\leqslant 3\\ -0.0442w^2+2.3573w+27.253 & 3<w\leqslant 19.74\\ 57.44 & w>19.74\end{cases}$
11	Temp. of controller	$x'_{R_{135}}(w)=\begin{cases}34.04 & w\leqslant 10.18\\ 0.2381w^2-4.6455w+57.015 & 10.18<w\leqslant 14.94\\ 57.44 & w>14.94\end{cases}$
12	Temp. of air outlet of base cabinet	$x'_{R_{136}}(w)=\begin{cases}22.94 & w\leqslant 8.56\\ 0.1858w^2-2.4542w+29.971 & 8.56<w\leqslant 14.94\\ 34.04 & w>14.94\end{cases}$
13	Active power	$x'_{R_{224}}(w)=\begin{cases}0 & w\leqslant 3\\ 8.6441\times 10^{-3}w^5-4.1874\times 10^{-1}w^4 +6.5649w^3-33.759w^2+ 63.25w+-25.079 & 3<w\leqslant 15\\ 850 & w>15\end{cases}$

Table 2
Fixed-limits range of the variables of the second type indices.

The variables of the second type indices	Lower limit value	Upper limit value
RPM of generator $x_{R_{124}}$ (rpm)	50	2000
Nacelle position $x_{R_{141}}$ (°)	−1080	1080
Vibration acceleration of nacelle $x_{R_{142}}$ (m/s^2)	0	3.34
Wind speed $x_{R_{211}}$(m/s)	3	25
Temp. of ambient $x_{R_{212}}$ (°C)	−20	50
Phase voltage $x_{R_{221}}$ (V)	324	385
Phase current $x_{R_{222}}$ (A)	0	980
Reactive power $x_{R_{223}}$ (kvar)	−100	100
Grid frequency $x_{R_{225}}$ (Hz)	48.5	51.5

primarily consists of the weight matrix calculation of the different layer indices, fuzzy membership functions, assessment criteria set, evaluation matrix calculations and defuzzification.

In the traditional fuzzy synthetic method, the constant weight of various layers and constant limited values of the assessment indices are typically used. To instantly assign the degree of importance of the assessment indices, a variable weight calculation of the various layers that considers the deterioration degree changes is proposed in this section. In the following description, this improved fuzzy synthetic assessment method is presented by using a variable weight on the different layers, dynamic limited values and deterioration degree functions of the characteristic variables.

3.1. Fuzzification of assessment indices

(1) *Selection of assessment indices and setting of criteria*:
In Fig. 2, the framework of the wind turbine real-time condition assessment system includes all assessment indices of a WTGS, and the assessment factor set R is proposed in light of different layer indices. For example, the assessment factor set of gearbox index factor set R_{11} can be expressed as: R_{11} = $\{R_{111}, R_{112}, R_{113}\}$.The assessment criteria set L can be established from actual operational conditions and divided into four categories, namely L = {excellent, good, alert, danger}=$\{l_1, l_2, l_3, l_4\}$. 'Excellent' indicates that the operational WTGS is in good condition and generating at high efficiency – all components are functioning in normal operational range. 'Good' indicates that the operational condition is within normal operating range, yet a few abnormal assessment indices may be allowed. 'Alert' indicates that the operational condition is beyond its normal operating range and

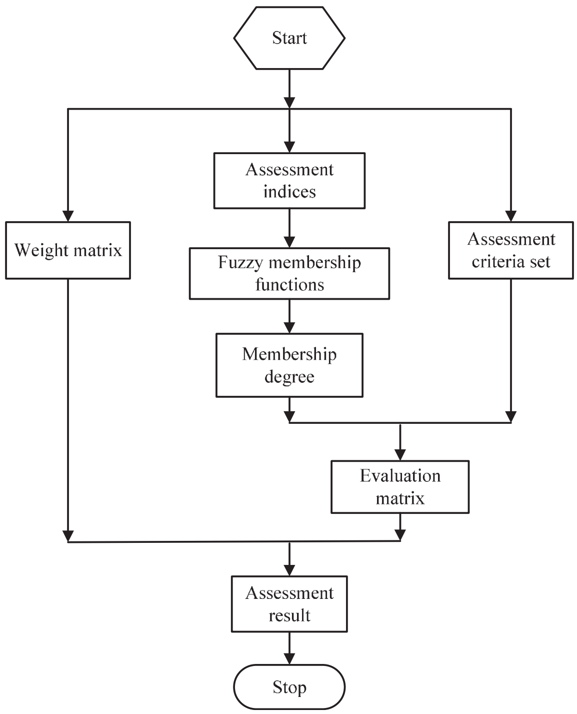

Fig. 4. Flowchart of the general fuzzy synthetic assessment method.

indicates a need for service of the affected component. The operator must determine whether any special action is warranted. 'Danger' indicates that the operational condition is beyond the acceptable operating limits and that continued operation at such levels could lead to imminent component damage and/or power system failure.

(2) *Fuzzy membership functions and calculation of evaluation matrix*:
The membership functions represent the degree to which the specified concentration belongs to the fuzzy set. The membership degrees of assessment indices at each level can be described quantitatively through a set of formulae of membership functions. Typical membership function shapes include trapezoidal, triangle, bell-shaped, Gaussian distribution, etc. [19]. Considering the operational characteristics of the wind turbine system, trapezoidal and triangular distributions are used in the presented membership function, as shown in Fig. 5.

The operating conditions are divided into four assessment levels according to range of degree of deterioration, namely Excellent, Good, Alert and Danger. As the values of deterioration degree increase, each index begins to experience different operating conditions from Excellent to Danger. The membership degree can also be determined by using the deterioration degree concept and the membership function. The value of membership function of each index related to the four assessment levels can be calculated by a set of formulae. For example, the membership function of the gearbox bearing temperature index R_{111} can be calculated as

$$v_{11}(g) = \begin{cases} 3.5 - 5.56g & 0.45 < g < 0.63 \\ 1 & g \leqslant 0.45 \\ 0 & g \geqslant 0.63 \end{cases}$$

$$v_{12}(g) = \begin{cases} 7.3 - 10g & 0.63 \leqslant g < 0.73 \\ 5.56g - 2.5 & 0.45 < g < 0.63 \\ 0 & g \geqslant 0.73 \text{ or } g \leqslant 0.45 \end{cases}$$

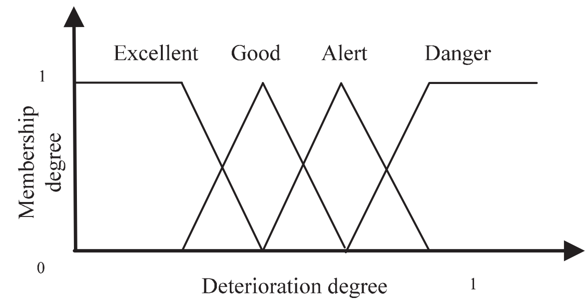

Fig. 5. Schematic diagram of the presented membership function.

$$v_{13}(g) = \begin{cases} 7.08 - 8.33g & 0.73 \leqslant g < 0.85 \\ 10g - 6.3 & 0.63 < g < 0.73 \\ 0 & g \geqslant 0.85 \text{ or } g \leqslant 0.63 \end{cases}$$

$$v_{14}(g) = \begin{cases} 1 & g \geqslant 0.85 \\ 8.33g - 6.08 & 0.73 < g < 0.85 \\ 0 & g \leqslant 0.73 \end{cases}$$

where $v_{11}(g) \sim v_{14}(g)$ denote the membership functions with conditions $l_1 \sim l_4$, respectively.

The synthetic fuzzy matrix V can be established by substituting the on-line monitoring data of each presented state indices into the membership functions. For example, the synthetic fuzzy evaluation matrix of gearbox index R_{11} can be calculated as:

$$V_{R11} = \begin{bmatrix} V_{R111} \\ V_{R112} \\ V_{R113} \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & v_{13} & v_{14} \\ v_{21} & v_{22} & v_{23} & v_{24} \\ v_{31} & v_{32} & v_{33} & v_{34} \end{bmatrix} \tag{5}$$

where v_{ij} (i = 1,2,3; j = 1,2,3,4) is the membership degree of the ith sub-project layer at the jth assessment index, respectively. The membership degrees $v_{i1} \sim v_{i4}$ correspond with the evaluated conditions $l_1 \sim l_4$, respectively.

3.2. Calculation of variable weight for different indices layers

To instantly attain the degree of importance of the assessment indices, the variable weight of various layers should be considered with the deterioration degree changes. However, in a multilayer synthetic assessment structure, the deterioration degree of the assessment indices cannot influence the weights of the sub-project layer indices and the project layer indices, making it difficult to obtain a reliable assessment result. For this study, different variable weights are proposed for the different indices layers and constant weights are used for the sub-project and project layer indices.

Considering the variation of the deterioration degrees, different variable weight calculations are proposed according to the different indices layers in the following variable weight equations.

$$\begin{cases} A_{R_{ijk}}(g_{R_{ij1}}, \ldots, g_{R_{ijd}}) = A^{(0)}_{R_{ijk}}(1 - g_{R_{ijk}})^{\delta-1} \Big/ \sum_{s=1}^{d} A^{(0)}_{R_{ijs}}(1 - g_{R_{ijs}})^{\delta-1} \\ A_{R_{ij}}(g_{R_{i1}}, \ldots, g_{R_{if}}) = A^{(0)}_{R_{ij}}(1 - g_{R_{ij}})^{\delta-1} \Big/ \sum_{s=1}^{f} A^{(0)}_{R_{is}}(1 - g_{R_{is}})^{\delta-1} \\ A_{R_{i}}(g_{R_{1}}, \ldots, g_{R_{p}}) = A^{(0)}_{R_{i}}(1 - g_{R_{i}})^{\delta-1} \Big/ \sum_{s=1}^{p} A^{(0)}_{R_{s}}(1 - g_{R_{s}})^{\delta-1} \end{cases} \tag{6}$$

where δ is a variable weight coefficient typically set to be -1 [21], $g_{R_{if}} = \max(g_{R_{ijd}})$ $(f = 1, 2, \ldots)$, $g_{R_p} = \max(g_{R_{ijd}})(p = 1, 2, \ldots)$, and d, f, and p are the number of assessment indices at the sub-project layer, the project layer and the destination layer, respectively. $A_{R_{ijk}}$, $A_{R_{ij}}$, and A_{R_i} are variable weight of different indices layers, respectively.

$A^{(0)}_{R_{ijk}}$, $A^{(0)}_{R_{ij}}$, and $A^{(0)}_{R_i}$ are constant weight values of different indices layers, determined through an analytical hierarchy process (AHP) [22] based on the maintenance records, fault statistics and expert experience [23], as listed in Table 3.

3.3. Procedure of the improved fuzzy synthetic assessment method

An improved fuzzy synthetic assessment flowchart is proposed as shown in Fig. 6. First, calculations of the deterioration degree must be performed to effectively solve the variation of deterioration degree of the indices layers.

The proposed fuzzy synthetic assessment method is composed of four steps; the explanation of each step is described as follows:

Step 1. The monitoring data of the WTGS is the input data of the proposed fuzzy synthetic assessment model.

Step 2. According to Eqs. (3) and (4), the deterioration degree of the bottom layer indices is calculated by using the input data. When the calculated deterioration degree is greater than 0.9, the final assessment result directly assigns the level of 'Danger'. Otherwise, the assessment process continues to obtain the results according to the fuzzy matrix calculation.

Step 3. The synthetic assessment result B matrix can be obtained as

$$B = A_R * V_R = [b_1, b_2, b_3, b_4]$$

where A_R is the variable weight of each index.

Step 4. To obtain the final condition assessment result, the calculated fuzzy matrix B can be transformed by using the defuzzification method. The maximum membership principle of the defuzzification method is adopted in this paper so that the calculated l_j ($j = 1,2,3,4$) corresponds to the $b_{max} = \max(b_j)$, where the maximal value of the B matrix denotes an assessment rank providing the final results of the real-time condition assessment for a WTGS.

4. Case study

To validate this improved fuzzy synthetic assessment method, two cases of a real-time condition assessment are investigated by using the on-line monitoring data of a 850 kW WTGS. In Case I, two groups of special data are selected, as shown in Table 4, to show the step-by-step assessment flow in detail. Group 1 data represent the normal operational condition and Group 2 data represent an abnormal condition where a gearbox fault occurs. In Case II, continual monitoring data are used to validate the real-time condition assessment method, and these assessment results are compared with a traditional fuzzy synthetic method in which a constant weight in the overall index layer and constant limited values of the assessment indices are used.

4.1. Case I

(1) Validation of condition assessment by using Group 1 data
According to the flow chart of the improved fuzzy synthetic condition assessment method shown in Fig. 6, the deterioration degree is initially calculated. All the calculated deterioration degrees are less than 0.9 for the Group 1 data, so the improved condition assessment process continues to calculate the fuzzy matrix. The process of fuzzy matrix B calculation can be finished by the following different layers assessment:

(a) Calculation of assessment indices in the sub-project layer

Based on the presented membership function as shown in section 3.1, the assessment matrix in the sub-project layer can be calculated as

$$V_{R_{11}} = \begin{bmatrix} 0.3870 & 0.6130 & 0.0000 & 0.0000 \\ 0.5411 & 0.4589 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix}; \quad V_{R_{12}} = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix};$$

$$V_{R_{13}} = \begin{bmatrix} 0.1255 & 0.8745 & 0.0000 & 0.0000 \\ 0.7422 & 0.2578 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.9226 & 0.0774 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.6978 & 0.3022 & 0.0000 & 0.0000 \end{bmatrix}; \quad V_{R_{14}} = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix};$$

$$V_{R_{21}} = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix}; \quad V_{R_{22}} = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix};$$

The corresponding variable weights can be calculated by using Eq. (6) as

$$A_{R_{11}} = [0.6744 \quad 0.1987 \quad 0.1269];$$

$$A_{R_{12}} = [0.4996 \quad 0.2153 \quad 0.2041 \quad 0.0810];$$

$$A_{R_{13}} = [0.2984 \quad 0.1700 \quad 0.1423 \quad 0.1487 \quad 0.1546 \quad 0.0861];$$

$$A_{R_{14}} = [0.6274 \quad 0.3726];$$

$$A_{R_{21}} = [0.8874 \quad 0.1126];$$

$$A_{R_{22}} = [0.1475 \quad 0.1512 \quad 0.1482 \quad 0.2781 \quad 0.2750];$$

The assessment result of the gear box index R_{11} can be given as

$$B_{11} = A_{R_{11}} * V_{R_{11}} = [0.4954 \quad 0.5046 \quad 0.0000 \quad 0.0000];$$

Similarly, the evaluation matrix of other indices can also be obtained as

Table 3
Weight calculation of the assessment indices for different indices layers.

Project layer indices	$A^{(0)}_{R_i}$	Sub-project layer indices	$A^{(0)}_{R_{ij}}$	$A^{(0)}_{R_{ijk}}$
R_1	0.7397	R_{11}	0.3022	[0.4258, 0.1509, 0.3233]
		R_{12}	0.2816	[0.3506, 0.3206, 0.2006, 0.1282]
		R_{13}	0.2919	[0.1487, 0.1604, 0.1987, 0.1897, 0.2158, 0.0867]
		R_{14}	0.1243	[0.6274, 0.3726]
R_2	0.2603	R_{21}	0.5538	[0.8874, 0.1126]
		R_{22}	0.4462	[0.1475, 0.1512, 0.1482, 0.2781, 0.2750]

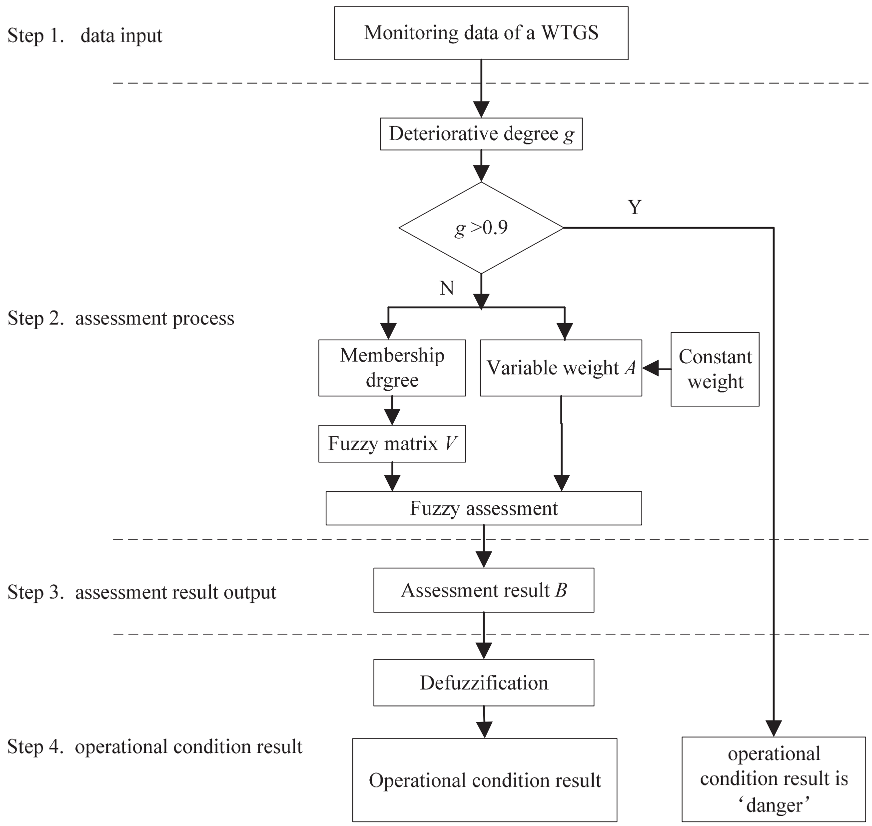

Fig. 6. Flowchart of the improved fuzzy synthetic assessment method.

$$V_{R_1} = \begin{bmatrix} B_{11} \\ B_{12} \\ B_{13} \\ B_{14} \end{bmatrix} = \begin{bmatrix} 0.4954 & 0.5046 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.6577 & 0.3423 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix};$$

$$V_{R_2} = \begin{bmatrix} B_{21} \\ B_{22} \end{bmatrix} = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 \\ 1.0000 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix}$$

(b) Calculation of assessment indices in the project layer
The corresponding variable weights in the sub-project layer can be obtained as

$$A_{R_1} = [0.3345 \quad 0.2180 \quad 0.3834 \quad 0.0641];$$
$$A_{R_2} = [0.5538 \quad 0.4462];$$

The evaluation matrix in the project layer can be calculated as

$$B_1 = A_{R_1} * V_{R_1} = [0.6999 \quad 0.3001 \quad 0.0000 \quad 0.0000];$$
$$B_2 = A_{R_2} * V_{R_2} = [1.0000 \quad 0.0000 \quad 0.0000 \quad 0.0000];$$

$$V_R = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix};$$

(c) Calculation of assessment indices in the destination layer
The corresponding variable weights can be calculated in the project layer as $A_R = [0.9486 \quad 0.0514]$, so the evaluation matrix in the destination layer can be obtained as $B = A_R * V_R = [0.7154 \quad 0.2846 \quad 0.0000 \quad 0.0000]$. Because the maximal value b_{max} is 0.7154 in the obtained assessment matrix B, the condition assessment result can be considered 'Excellent' for this WTGS at this point, which concurs with the results of the real-time monitoring Group 1 data.

Table 4
Two group monitoring data of the 850 kW WTGS.

No.	The variables of assessment indices	On-line monitoring data	
		Group 1	Group 2
1	Temp. of gearbox bearing $x_{R_{111}}$ (°C)	61.5	83.5
2	Temp. of gearbox oil cooled $x_{R_{112}}$ (°C)	35.0	58.1
3	Temp. of gearbox oil $x_{R_{113}}$ (°C)	52.1	79.9
4	Temp. of generator bearing $x_{R_{121}}$ (°C)	50.2	81.4
5	Temp. of generator winding $x_{R_{122}}$ (°C)	60.7	125.5
6	Temp. of generator cooling$x_{R_{123}}$ (°C)	33.6	52.1
7	RPM of generator $x_{R_{124}}$ (rpm)	1235	1796
8	Temp. of reactor $x_{R_{131}}$ (°C)	100.1	134.4
9	Temp. of capacitor $x_{R_{132}}$ (°C)	41.7	76.6
10	Temp. of IGBT $x_{R_{133}}$ (°C)	43.0	68.4
11	Temp. of rectifier $x_{R_{134}}$ (°C)	47.7	73.4
12	Temp. of controller $x_{R_{135}}$ (°C)	25.4	40.4
13	Temp. of air outlet of base cabinet $x_{R_{136}}$ (°C)	28.8	39.0
14	Nacelle position $x_{R_{141}}$ (°)	−340	153
15	Vibration acceleration of nacelle $x_{R_{142}}$ (m/s^2)	0.1568	0.4116
16	Wind speed $x_{R_{211}}$ (m/s)	8.23	12.73
17	Temp. of ambient $x_{R_{212}}$ (°C)	12.5	23.4
18	Phase voltage $x_{R_{221}}$ (V)	356.44	353.10
19	Phase current $x_{R_{222}}$ (A)	232.96	332.40
20	Reactive power $x_{R_{223}}$ (kvar)	−13.8	−40.4
21	Active power $x_{R_{224}}$ (kW)	326.40	733.29
22	Grid frequency $x_{R_{225}}$ (Hz)	49.81	50.12

(2) Validation of condition assessment by using the Group 2 data
Calculating the deterioration degrees of the Group 2 data in Table 4 show that the deterioration degree of $R_{111}(g_{R_{111}} = 0.9060)$ is larger than 0.9, so that the final assessment result $B = [0.0000 \quad 0.0000 \quad 0.0000 \quad 1.0000]$

Table 5
Condition assessment results of the 850 kW WTGS from January 2009 to September 2009.

No.	Assessment indices	On-line monitoring data					
		1	2	3	4	5	6
1	R_{111} (°C)	70.1	59.5	75.6	72.9	77.6	50.7
2	R_{112} (°C)	31.0	26.3	38.8	33.4	45.8	32.3
3	R_{113} (°C)	59.2	49.4	68.1	63.1	70.9	48.5
4	R_{121} (°C)	49.4	50.6	67.5	59.3	69.6	48.2
5	R_{122} (°C)	89.7	58	122.7	102.6	111.1	51.0
6	R_{123} (°C)	27.3	39.3	31.9	27.2	34.5	37.8
7	R_{124} (rpm)	1640	1104	1740	1729	1740	46
8	R_{131} (°C)	94.6	80.3	128.8	106	143.9	81.6
9	R_{132} (°C)	51.2	30.4	76.9	61.2	78.6	31.7
10	R_{133} (°C)	49.5	27.8	56.5	48.9	68.0	20.0
11	R_{134} (°C)	50.3	28.1	58	51.0	58.7	23.7
12	R_{135} (°C)	19.4	15.9	22.4	17.9	27.1	23.1
13	R_{136} (°C)	18.0	20.2	23.7	17.0	25.1	29.5
14	R_{141} (°)	−223	−707	−419	−766	−411	−1092
15	R_{142} (m/s^2)	0.2940	0.0882	0.0657	0.6958	0.6566	0.3724
16	R_{211} (m/s)	11.51	5.87	15.56	12.32	16.36	5.37
17	R_{212} (°C)	4.3	4.4	0.6	−2.7	7.6	12.8
18	R_{221} (V)	368.69	361.53	372.86	371.21	362.79	359.13
19	R_{222} (A)	837.61	104.64	848.45	852.05	798.91	38.12
20	R_{223} (kvar)	−34.0	−16.5	−41.7	−39.5	−44.9	−23.5
21	R_{224} (kW)	723.35	83.96	854.72	903.93	798.91	2.29
22	R_{225} (Hz)	50.00	49.97	50.01	49.96	50.06	50.07
Assessment results by using the improved fuzzy model		[0.3887, 0.2978, 0.2344, 0.0790]	[0.2786, 0.3673, 0.1697, 0.1844]	[0.2357, 0.1581, 0.5242, 0.0821]	[0.0000, 0.0000, 0.0000, 1.0000]	[0.0000, 0.0000, 0.0000, 1.0000]	[0.0000, 0.0000, 0.0000, 1.0000]
		Excellent	Good	Attention	Danger	Danger	Danger
Assessment results by using the traditional fuzzy model		[0.4863, 0.3199, 0.1615, 0.0099]	[0.5057, 0.3858, 0.0538, 0.0323]	[0.2510, 0.2614, 0.2881, 0.1772]	[0.3566, 0.3047, 0.2801, 0.0362]	[0.1973, 0.2479, 0.3099, 0.2225]	[0.5827, 0.1944, 0.1428, 0.0577]
		Excellent	Excellent	Attention	Excellent	Attention	Excellent

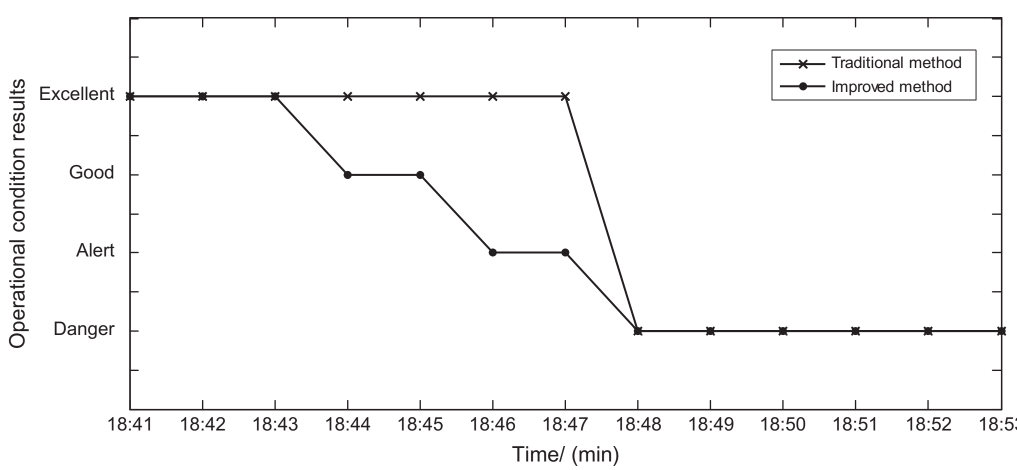

Fig. 7. Continuous real-time condition assessment results of the 850 kW WTGS from 18:41 to 18:53 in September 29, 2009.

can be directly obtained with the improved fuzzy synthetic assessment method. It can conclude that the condition assessment result is at a 'Danger' level for this WTGS at this point, which concurs with the results of the real-time monitoring Group 2 data – the temperature of both the gearbox bearing and the gearbox oil approach their upper limit values.

4.2. Case II

The January to September 2009 on-line monitoring data of the 850 kW WTGS are used to further validate the improved fuzzy synthetic method. The real-time condition assessment results are shown in Table 5. The improved fuzzy synthetic assessment method results may be more appropriate in reflecting the operational condition than that of the traditional fuzzy model. For example, in the 4th monitoring data the real-time condition should be a level of 'Danger' because the active power is beyond the upper limit value. However, the traditional fuzzy method obtained a condition assessment result level of 'Excellent.'

In addition, to demonstrate the real-time condition response of the proposed assessment model, the on-line monitoring data are also used to investigate a specific incident on September 29, 2009, where the WTGS stops at 18:48 due to the high temperature of the generator winding. Fig. 7 shows the continuous operational condition results from 18:41 to 18:53 using both the traditional and the improved fuzzy methods. The improved assessment method accurately charted the real-time condition change compared to the traditional fuzzy method; the adverse condition could have been foreseen with the improved fuzzy method – a helpful improvement to the operational reliability of the WTGS.

5. Conclusions

Based on the WTGS control system monitoring quantities, a framework of real-time condition assessment was proposed including multi-layer indices. The dynamic limits and the deterioration degree functions of the assessment for the characteristic variables were determined by analyzing the monitoring data of this WTGS. An improved fuzzy synthetic condition assessment method was proposed that utilized the concepts of deterioration degree, dynamic limited values and variable weight calculations of the assessment indices. By using the normal and abnormal operational data of an actual WTGS, the results of the condition assessment with the improved fuzzy synthetic method demonstrate accurate reliability with actual conditions. Furthermore, based on the assessment of continual operational data from an actual WTGS, the improved assessment method can more accurately predict changes in operational condition than a traditional fuzzy synthetic method. The proposed fuzzy synthetic condition assessment method may be helpful in improving the operational reliability of a WTGS. Even though the on-line monitoring data of an actual 850 kW WTGS is only testified in this paper, the improved fuzzy synthetic method could be still used to assess the condition for different types of WTGS with the real-time data. Considering many physical quantities of different components need to be monitored in the operational WTGS, the extracted key characteristic variables need to be further investigated in the future research.

Acknowledgements

The research work is supported by the Program for New Century Excellent Talents in University (NCET-10-0878), by the Fundamental Research Funds for the Central Universities (CDJZR 10150014) and by the Scientific Research Foundation of State Key Laboratory of Power Transmission Equipment & System Security and New Technology (2007DA10512710101). The authors are grateful for this support. Additionally, the authors would like to thank the Chongqing KK-Qianwei Wind Power Equipment Company for providing information on the real-time monitoring data and practical control system platform of the WTGS.

References

[1] Li H, Chen Z. Overview of different wind generator systems and their comparisons. IET Renewable Power Generation 2008;2(2):123–38.
[2] Sebastian R. Modelling and simulation of a high penetration wind diesel system with battery energy storage. Int J Electr Power Energy Syst 2011;33:767–74.
[3] Spinato F, Tavner PJ, van Bussel GJW, Koutoulakos E. Reliability of wind turbine subassemblies. IET Renewable Power Generation 2009;3(4):1–15.
[4] Tascikaraoglu A, Uzunoglu M, Vural B, Erdinc O. Power quality assessment of wind turbines and comparison with conventional legal regulations: a case study in Turkey. Appl Energy 2011;88:1864–72.
[5] Xiang JP, Simon W. Assessment of condition monitoring techniques for offshore wind farms. J Solar Energy Eng 2008;130:0310041–49.
[6] Zaher A, McArthur SDJ, Infield DG. Online wind turbine fault detection through automated SCADA data analysis. Wind Energy 2009;12(6):574–93.
[7] Arabian-Hoseynabadi H, Oraee H, Tavner PJ. Failure modes and effects analysis (FMEA) for wind turbines. Int J Electr Power Energy Syst 2010;32(7):817–24.
[8] Arabian-Hoseynabadi H, Oraee H, Tavner PJ. Wind turbine productivity considering electrical subassembly reliability. Renewable Energy 2010;35(1): 190–7.
[9] Andrew Kusiak, Anoop Verma. A data-driven approach for monitoring blade pitch faults in wind turbine. IEEE Trans Sustainable Energy 2011;2(1):87–96.
[10] Zijun Zhang, Anoop Verma, Andrew Kusiak. Fault analysis and condition monitoring of the wind turbine gearbox. IEEE Trans Energy Conversion 2012;27(2):526–35.
[11] Kassem Ahmed M. Robust voltage control of a stand alone wind energy conversion system based on functional model predictive approach. Int J Electr Power Energy Syst 2012;41(1):124–32.
[12] Ghedamsi K, Aouzellag D. Improvement of the performances for wind energy conversions systems. Int J Electr Power Energy Syst 2010;32(9):936–45.
[13] Nilsson J, Bertling L. Maintenance management of wind power systems using condition monitoring systems – life cycle cost analysis for two case studies. IEEE Trans Energy Convers 2007;22(1):223–9.
[14] Yang W, Tavner PJ, Crabtree CJ, Wilkinson M. Cost effective condition monitoring for wind turbines. IEEE Trans Ind Electr 2010;57(1):263–71.
[15] Zaher A, McArthur SDJ, Infield DG, Patel Y. Online wind turbine fault detection through automated SCADA data analysis. Wind Energy 2009;12(6):574–93.
[16] Hameeda Z, Honga YS, Choa YM, Ahnb SH, Song CK. Condition monitoring and fault detection of wind turbines and related algorithms: a review. Renewable Sustainable Energy 2009;13(1):1–39.
[17] McMillan D, Ault GW. Condition monitoring benefit for onshore wind turbines: sensitivity to operational parameters. IET Renewable Power Generation 2008;2(1):60–72.
[18] Zhang Xi Rong, Li Zhi, Shen Yao Jie. Research on risk assessment of wind power project. In: Proceedings of the international conference on informatics, cybernetics, and computer engineering (ICCE2011), Melbourne, Australia; November 2011.
[19] Qian Z, Yan Y. Fuzzy synthetic method for life assessment of power transformer. IEE Proc Sci Meas Technol 2004;151(3):175–80.
[20] Wind turbine generator systems part 12: wind turbine power performance testing. IEC61400-12;1998.
[21] Yujiong Gu, Kunliang Chen, Kun Yang. Fuzzy comprehensive evaluation method based on analytic hierarchy process for fait risk analysis of power plant equipment. In: Proceedings of the international conference on fuzzy systems and knowledge discovery, Shandong, China; October 2008.
[22] Chen MK, Wang SC. The critical factors of success for information service industry in developing international market: using analytic hierarchy process (AHP) approach. Expert Syst Appl 2010;37(1):694–704.
[23] Ribrant J, Bertling LM. Survey of failures in wind power systems with focus on Swedish wind power plants during 1997–2005. IEEE Trans Energy Convers 2007;22(1):167–73.