Abstract—This paper proposes a method for steam turbine-generator fault diagnosis using grey clustering analysis (GCA). According to the field records, diagnostic information can be provided to monitor mechanical condition by the spectrum of the vibration signal. Frequency-based features are computed by fast Fourier transformation (FFT), the frequency ranges are <0.4f, 1f, 2f, 3f, and >3f. The maximum and minimum values of power spectrum indicate mechanical vibration fault at a particular frequency, and frequency patterns are applied to diagnose faults. For numerical tests with practical filed records, test results were conducted to show the proposed method demonstrates computational efficiency and high accuracy.

Indexing Terms—Steam Turbine-Generator, Grey Clustering Analysis (GCA), Fast Fourier Transformation (FFT).

I. Introduction

Turbine generator is a major device of the thermal plants to convert heat energy of steam into electrical energy through mechanical energy. The generator fault not only damages the generator itself, but also causes outages and loss of profits. With high-temperature, high-pressure and factors such as thermal fatigues, many components may go wrong, which will not only lead to great economy loss, but sometimes a threat to social security. Independent Power Producers (IPPs) need to provide a high quality service to retain their customers. So the fault diagnosis becomes an important research subject more and more. It is necessary to detect generator faults and take immediate actions to cut the loss. With the complexities, coupling effects and some uncertain factors on turbine generator's structure, the fault diagnosis is difficult to detect by theoretical analysis or mathematical model. Various artificial intelligent (AI) techniques have been proposed for fault diagnosis, such as the artificial neural networks (ANNs) [1]-[3], fuzzy logic (FL) theorem [4], fuzzy neural networks (FNN) [5] and expert systems [6]. In this research, the major fault diagnosis scheme is based on the vibration feature of faulty vibration, which is effective and easy to use.

Wavelet neural network (WNN) has been applied on steam turbine-generator fault diagnosis. GCA and Grey Clustering Analysis (GCA) are useful methods to deal with the problems of limited, deficient, and or no rules available for data processing. It is a useful method to deal with the problems of limited, deficient, and or no rules available for data processing. Its analysis makes use of minor data and does not demand strict statistical procedures and inference rules. In this paper, a diagnostic scheme based on GCA is applied to steam turbine-generator fault diagnosis. GCA has a function of mathematical operation for processing numerical data without adjusting any parameter. For numerical tests, the proposed method demonstrates computational efficiency, easy implementation, and high accuracy for practical tests.

II. Problem Description

Power plants convert the fuel energy into mechanical energy, and then converted into electrical energy. Heat engines converting steam or gas energy into mechanical energy, are classified as steam engine or steam turbine by using either piston or rotary design. In the thermal power plants, steam turbines are generally employed. To increase the efficiency, the temperature and pressure are gradually raised to high levels [13]. Water flows through steel pipes designed to withstand high steam pressures. The chemical fuel such as coal, gas, or atomized oil is burned in the furnace. Steam is produced in the boiler. Turbine-generator is major components of the thermal plant and consists of three parts: the turbine, generator and exciter. The turbine can also be divided into the high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP) parts. All of these sections are girdled by the bearings that provide most of the diagnostic information [14].

The generator fault can be classified into three types including electrical fault, mechanical vibration fault, and cooling system fault. First two are the common incipient
Vibration signals are collected from data acquisition mechanical condition and avoiding defects development. Measures are carried out to take all possible phase analysis, precession analysis, and probability the vibration waveform analysis, frequency analysis, automatically using the trip system. For fault diagnosis, regulated with restriction to shut down the operation rotor and the bearing position. The shaft vibration is detected the condition of turbine generator during operation. The displacement meter and accelerometer are set at the expansion meter, and shaft vibration meter, are used to detect the condition of turbine generator during operation. The protection should quickly trip the main circuit breaker to disconnect the machine from the rest of the system and disconnect the field winding from the exciter. The protection is provided by a percentage-differential relay for winding short-circuit faults. Mechanical vibration fault has imbalance, no orderliness, and rotor crack. The monitor instrument such as shaft position meter, shaft eccentricity meter, speed meter, difference expansion meter, and shaft vibration meter, are used to detect the condition of turbine generator during operation. The displacement meter and accelerometer are set at the rotor and the bearing position. The shaft vibration is regulated with restriction to shut down the operation automatically using the trip system. For fault diagnosis, the vibration waveform analysis, frequency analysis, phase analysis, precession analysis, and probability density analysis are carried out to take all possible measures.

Vibration is an important indicator for monitoring mechanical condition and avoiding defects development. Vibration signals are collected from data acquisition

Fig. 1. Power spectra of typical fault type in the frequency domain

faults in the generator. Electrical fault has rotor excitation short circuit, stator winding grounded fault, and stator winding short circuit involving three-phase fault or line-to-line fault. Rotor excitation short circuit causes unbalance magnetic pull that acts on the rotor and stator and causes vibration. When a short circuit occurs at the stator winding, or between a stator winding and ground, the protection should quickly trip the main circuit breaker to disconnect the machine from the rest of the system and disconnect the field winding from the exciter. The protection is provided by a percentage-differential relay for winding short-circuit faults. Mechanical vibration fault has imbalance, no orderliness, oil-membrane oscillation, misalignment, and rotor crack. The monitor instrument such as shaft position meter, shaft eccentricity meter, speed meter, difference expansion meter, and shaft vibration meter, are used to detect the condition of turbine generator during operation. The displacement meter and accelerometer are set at the rotor and the bearing position. The shaft vibration is regulated with restriction to shut down the operation automatically using the trip system. For fault diagnosis, the vibration waveform analysis, frequency analysis, phase analysis, precession analysis, and probability density analysis are carried out to take all possible measures.

Vibration is an important indicator for monitoring mechanical condition and avoiding defects development. Vibration signals are collected from data acquisition

III. Steam Turbine-Generator Fault Diagnostic Procedure

A. Grey Clustering Analysis (GCA)

If a steam turbine-generator operates under the normal condition, vibration conditions are usually small and constant. When a fault occurs or gradually grows, the vibration signals have morphology changes. The vibration phenomena are collected from data acquisition system. The spectrum varies with different conditions including normal condition, oil-membrane oscillation, imbalance, and no orderliness, and power spectra are selected in the frequency range [0.4f, 1f, 2f, 3f, and >3f]. Various conditions occupy different lower and upper limits as shown in Figure 1. Diagnostic information can be extracted from the spectrum of the vibration signal. Various ranges of frequency spectra are used to identify the faults, but it is difficult to describe the uncertain boundaries in the numerical data such as the lower and upper values. Therefore, GCA is introduced to develop the diagnostic procedure. Like the Fuzzy approach, different ranges of frequency spectra are described by the “whiten-weight function”. The common ones are triangular and trapezoidal functions. The trapezoidal functions are used as shown in Figure 2. Parameter b is the lower/upper value of vibration frequency f. Parameters a and c are boundary values, which can be determined [16]

\[
(b-a)=(c-b)=b\times5\% 
\]  

(1)

\[ F_1(f) \] and \[ F_2(f) \] are the whiten-weight functions which typically fall within [0,1]. Weighted values \[ F_1(f) \] and

![Vibration Frequency](image-url)
Fig. 3. Whiten-weight functions for vibration frequencies $<0.4f$, $1f$, $2f$, $3f$, and $>3f$.

$F_k(f_i)$ are complements. Whiten-weight functions for pre-selected frequencies are defined by lower and upper values as shown in Figure 3.

For unknown input vector $F=[f_1, f_2, f_3, \ldots, f_n]$, $i=1, 2, 3, \ldots, n$, $n$ is the number of the vibration frequency ($n=5$ in our study). Whiten-weighted values for each vibration frequency (VF) in the different ranges are evaluated by

$$VF_i = [F_1(f_i), F_2(f_i), \ldots, F_K(f_i)]$$  \hspace{1cm} (2)

where $k=1, 2, 3, \ldots, K$, $K$ is the number of whiten-weight functions for each vibration frequency ($K=4$ in our study). Then $m$ grey clusters for each vibration frequency are evaluated by

$$G_i = [g^i_j] = VF_iW_i$$

Compute the final grey grade $FG_j$ by

$$FG_j = \max \frac{1}{n} \sum_{i=1}^{n} g^i_j, \quad j=1, 2, 3, \ldots, m$$ \hspace{1cm} (6)

Then find the maximum value, $FG_{max} = \max \{FG_1, FG_2, FG_3, \ldots, FG_m\}$. The maximum value $FG_{max}$ indicates the fault type. In this paper, the major classes include: $FG_1$: Oil-membrane Oscillation, $FG_2$: Imbalance, $FG_3$: No Orderliness, and $FG_4$: Normal Condition.
Table 1. Tested data of steam-turbine generator sets

<table>
<thead>
<tr>
<th>Generator Number</th>
<th>&lt;0.4f</th>
<th>1f</th>
<th>2f</th>
<th>3f</th>
<th>&gt;3f</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.35</td>
<td>12.15</td>
<td>1.94</td>
<td>2.30</td>
<td>3.67</td>
</tr>
<tr>
<td>2</td>
<td>4.43</td>
<td>11.02</td>
<td>3.20</td>
<td>1.30</td>
<td>2.43</td>
</tr>
<tr>
<td>3</td>
<td>3.29</td>
<td>11.61</td>
<td>1.24</td>
<td>0.90</td>
<td>1.30</td>
</tr>
<tr>
<td>4</td>
<td>5.72</td>
<td>12.31</td>
<td>3.62</td>
<td>1.50</td>
<td>0.59</td>
</tr>
<tr>
<td>5</td>
<td>3.24</td>
<td>42.66</td>
<td>2.16</td>
<td>1.10</td>
<td>0.54</td>
</tr>
<tr>
<td>6</td>
<td>6.32</td>
<td>15.23</td>
<td>3.56</td>
<td>2.30</td>
<td>3.19</td>
</tr>
<tr>
<td>7</td>
<td>0.54</td>
<td>37.80</td>
<td>2.70</td>
<td>2.70</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>1.51</td>
<td>52.92</td>
<td>6.59</td>
<td>2.50</td>
<td>2.54</td>
</tr>
<tr>
<td>9</td>
<td>2.43</td>
<td>54.49</td>
<td>4.64</td>
<td>0.80</td>
<td>1.78</td>
</tr>
<tr>
<td>10</td>
<td>0.54</td>
<td>48.82</td>
<td>6.64</td>
<td>3.90</td>
<td>1.51</td>
</tr>
<tr>
<td>11</td>
<td>0.81</td>
<td>52.00</td>
<td>6.43</td>
<td>3.60</td>
<td>1.89</td>
</tr>
<tr>
<td>12</td>
<td>1.24</td>
<td>49.79</td>
<td>4.64</td>
<td>1.00</td>
<td>2.27</td>
</tr>
<tr>
<td>13</td>
<td>1.78</td>
<td>22.46</td>
<td>23.8</td>
<td>19.0</td>
<td>8.59</td>
</tr>
<tr>
<td>14</td>
<td>0.92</td>
<td>30.08</td>
<td>22.0</td>
<td>16.0</td>
<td>5.67</td>
</tr>
<tr>
<td>15</td>
<td>0.65</td>
<td>21.98</td>
<td>26.2</td>
<td>18.0</td>
<td>11.1</td>
</tr>
<tr>
<td>16</td>
<td>1.13</td>
<td>24.46</td>
<td>22.3</td>
<td>15.0</td>
<td>15.8</td>
</tr>
<tr>
<td>17</td>
<td>0.92</td>
<td>26.08</td>
<td>26.0</td>
<td>20.0</td>
<td>11.4</td>
</tr>
<tr>
<td>18</td>
<td>1.08</td>
<td>20.25</td>
<td>25.4</td>
<td>17.0</td>
<td>11.9</td>
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<tr>
<td>19</td>
<td>0.54</td>
<td>8.10</td>
<td>2.70</td>
<td>2.70</td>
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<tr>
<td>20</td>
<td>0.27</td>
<td>8.64</td>
<td>1.08</td>
<td>1.10</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Note: f (Hz) is the frequency of the generator rotor.

B. Fault Diagnostic Procedure

The GCA based classifier is developed to work with the existing diagnosis equipment. The FDP consists of two stages: (a) preprocessing stage and (b) pattern recognition stage, as shown in Figure 4. Vibration signals from data acquisition system are collected and transferred to computer. Features in the frequency domain are extracted by FFT method. The incipient faults can be revealed by vibration frequency spectrum. Abnormal vibration information can be detected at pattern recognition stage by continuously monitoring. If new practical records are produced new boundary values, lower/upper boundaries of white-weight functions can be adjusted continually. The decision boundaries can be easily modified by equation (1). Its analysis makes use of minor data, and also has a function of mathematical operation for processing numerical data without any inference rule.

IV. Test Results

The proposed fault diagnostic procedure was designed on a PC Pentium-IV 2.4GHz with 480MB RAM and Matlab software. Using the practical records, the proposed procedure provides highly confident results for judging the faults. To demonstrate the effectiveness of the proposed procedure, twenty recorded data from steam-turbine generator sets are tested as shown in Table 1 [14].

For generator number 1, the maximum grey grade indicates the fault, and confirms that the fault is oil-membrane oscillation. CGA takes 1.875 seconds CPU Time to detect 20 tests, and overall tests results are shown in Figure 6. Maximum value indicates the white or light gray and corresponds to the fault. The GCA based classifier promises the results with 100% accuracy.

B. Study Case 2

The same twenty recorded data are also used to test for four fault types. In practical measurement, signals may be disturbed by noise such as quantification error. Adding −30% to +30% noises to the original patterns,
The test results show that the proposed method can work with noisy background. For example, Figure 7 shows the frequency spectrum for the test records of Imbalance. Using the record of generator number 7, the input data are added +10% noise to the vibration frequencies. The diagnostic procedures are:

Step 1: Vibration spectrum:
\[ F = [0.5940, 41.5800, 2.9700, 2.9700, 0.0000] \]

Step 2: Whiten-weighted values:
\[ VF_1 = [0.0000, 1.0000, 1.0000, 0.0000] \]
\[ VF_2 = [0.0000, 0.0000, 1.0000, 0.0000] \]
\[ VF_3 = [1.0000, 1.0000, 0.0000, 1.0000] \]
\[ VF_4 = [0.0000, 1.0000, 0.0000, 1.0000] \]
\[ VF_5 = [0.0000, 1.0000, 0.0000, 0.0000] \]

Step 3: Grey cluster for each vibration frequency:
\[ G_1 = [0.0000, 1.0000, 1.0000, 0.0000] \]
\[ G_2 = [0.0000, 0.0000, 1.0000, 0.0000] \]
\[ G_3 = [1.0000, 1.0000, 0.0000, 1.0000] \]
\[ G_4 = [0.0000, 1.0000, 0.0000, 1.0000] \]

Step 4: Final grey grades:
\[ \sigma = [FG_1, FG_2, FG_3, FG_4] \]
\[ = [0.2000, 0.8000, 0.4000, 0.4000] \]

The fault is judged by \( \max(\sigma) = FG_2 = 0.8000 \). Maximum value indicates the “Imbalance” fault.

The maximum grey grade 0.8000 indicates the fault, and confirms that the fault is imbalance. Overall test results for twenty steam-turbine generator sets are shown in Figure 8. This study case confirms that the overall accuracies are also 100% with +10% noise.

V. Discussions and Conclusion

The fault diagnostic procedure based on GCA has been presented to mechanical vibration fault diagnosis for steam turbine-generators. The proposed method could avoid the determination of the linguistic variables, membership functions, inference rules, and parameters assignment, and is easy to implement in the portable device. Since the mathematical operation for numerical data without adjusting any parameter, GCA requires less computation time, and it is a useful method to deal with the problems of limited, deficient, and no rules available for data processing. Its analysis makes use of minor data to construct the whiten-weight functions and does not demand strict statistical procedures. Random adding noises to each selected vibration frequency with “−50%” to “+50%” noises (symbol “+” means positive noise and symbol “−” means negative noise). With 20 generators, the test shows that proposed method has 100% detection accuracy under noisy background with “−15%” to “+20%” noises, and the accuracies decay as positive/negative noises increase (Accuracy < 80%). To develop an assistance tool, the proposed method can be
was born in 1972. He received the B.S. degree in Power Delivery, Vol.16, No.4, 2001, pp. 473-477.


Biographies

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