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Monitoring Wind Turbine Condition by the Approach of Empirical Mode Decomposition

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***Abstract*-An efficient condition monitoring system is indispensable to a large offshore wind turbine (WT) as it suffers higher reliability risk being exposed to extreme running environment and subject to constantly variable loadings, however difficult to access for fault repair. Today, the majority condition monitoring techniques for WT are borrowed from other industry fields where they achieve success. However, to date these techniques have not proved entirely satisfactory in wind industry. The reasons are various. But one of the main reasons is lack of a proper approach to the accurate analysis of WT signals, which are non-stationary in both time and frequency. The inaccurate analysis of WT signals results in frequent spurious alarms, which cause unnecessary shut down of machines and seriously disturb the normal production of wind farms. Aim at improving this situation, a new technique is developed in this work through analyzing the total power signals measured from the terminals of the WT generator by using the approach of Empirical Mode Decomposition (EMD). In comparison with those conventional Fourier transform-based techniques that are being popularly used today in wind industry, the EMD is more ideal for processing the non-stationary, nonlinear WT signals attribute to its intrinsic locally adaptive property. Additionally, the computational algorithm of the EMD is more efficient than that of previous wavelet analysis, which enables the EMD more suitable for use in online condition monitoring systems. The proposed approach has been experimentally validated on a deliberately designed WT test rig with a 3-phase induction generator. It has been proved that the proposed strategy is valid for detecting both drive train mechanical and generator electrical faults occurring in all types of WTs whether geared or direct-drive.**

I. INTRODUCTION

Although wind energy conversion is simple in concept, the design and installation of a wind turbine, especially those large wind turbines going offshore, are quite complex and costly. Additionally, wind turbine is liable to failure as it usually works in aggressive working environments and is constantly subject to variable loadings. Once the machine breaks down due to failure at an unscheduled time, the breakdown time will be long and therefore cause great economic losses. All above reasons highlight the importance and significance of applying a condition monitoring system to a WT, especially to those large, modern and offshore ones. However, most condition monitoring techniques currently adopted in wind industry are borrowed from other fields [1]. They are used without sufficiently considering the peculiarities of WT signals, which are non-stationary, and moreover, nonlinear in both time and frequency. In consequence, to date the commercially available wind turbine condition monitoring systems have not demonstrated their expected values satisfactorily in wind farms. Contrarily, the productions of wind farms are often disturbed by the false alarms given off by the systems. The inaccurate analysis of WT signals is one of the root causes of above phenomena. The Fourier transform(FT)-based techniques are popularly adopted in wind industry [2]. However, the FT is not an ideal tool for analyzing WT signals due to their well-known intrinsic shortcomings in processing non-stationary signals. Wavelet analysis has been well proved a powerful tool for processing non-stationary signals. But unfortunately, it does not show satisfactory in dealing with the signals with nonlinear features. Moreover, its algorithm is not efficient enough for use online, although some efforts have been made [3, 4, 5]. In view of above reasons, a new WT condition monitoring technique is developed in this work by the approach of the EMD, which is distinguished by both its excellent capability in processing non-stationary/nonlinear signals and its efficient computational algorithm [6].

II. BRIEF REVIEW OF THE EMD AND ITS MERITS

As an innovative time series analysis tool developed by Huang et al. [6], the EMD has proven to be an important alternative to traditional signal processing techniques such as the FT and wavelet transforms, and shown great success in dealing with non-stationary, nonlinear signals like those collected from WTs. It decomposes the signal into a finite number of Intrinsic Mode Functions (IMFs) adaptively without needing any prior knowledge about the signal. An IMF satisfies the conditions: (1) The numbers of extrema and zero-crossing are same or differ by 1 at most; (2) The upper and lower envelopes are symmetric with respect to zero. Assume a WT signal $x(t)$, the IMFs embedded in it may be extracted through an elegant EMD algorithm as depicted in the following.

Firstly, identify all local maxima and minima in $x(t)$, interpolate the extrema via cubic splines to use as the upper envelope $U(t)$ and the lower envelope $L(t)$ of $x(t)$. Then, calculate the mean of the envelopes, i.e.

$$m(t)=\frac{U(t)+L(t)}{2} \tag{1}$$

Subtract $m(t)$ from $x(t)$, have

$$h_{1,0}(t)=x(t)-m(t) \tag{2}$$

If $h_{1,0}(t)$ is not an IMF, the following sifting process will be continually repeated until an IMF is achieved, i.e.

$$h_{1,k}(t)=h_{1,k-1}(t)-m_{1,k-1}(t) \tag{3}$$

where $k \geq 1$ is a positive integer, $m_{1,k-1}(t)$ represents the mean of the upper and lower envelopes of $h_{1,k-1}(t)$.

Once $h_{1,k}(t)$ has been an IMF, let

$$c_1(t)=h_{1,k}(t) \tag{4}$$

$$r_1(t)=x(t)-c_1(t) \tag{5}$$

where $c_1(t)$ represents the first IMF of $x(t)$ derived using the EMD.

Then, regard $r_1(t)$ as the original time series for the new iteration and apply the aforementioned sifting process to $r_1(t)$ to derive the second IMF $c_2(t)$. After obtaining $c_2(t)$, subtract it from $r_1(t)$ using the equation

$$r_{i+1}(t)=r_i(t)-c_{i+1}(t) \tag{6}$$

where $i \geq 1$ is a positive integer.

Likewise, the same sifting process will be iterated once again by taking $r_{i+1}(t)$ as the new original data until the resultant $r_{i+1}(t)$ has been a constant or a monotonic function. Finally, the inspected signal $x(t)$ may be expressed as

$$x(t)=\sum_{j=1}^{N} c_j(t)+r_N(t) \tag{7}$$

In comparison with traditional signal processing methods such as Fourier spectral analysis and wavelet transforms, the EMD possesses the following merits:

(1) The EMD decomposes the signal adaptively without giving any assumption on the inspected data. On the contrary, both traditional Fourier transform and wavelet transforms assume the data linear, which is usually not true in reality. Besides this, Fourier transform also requires the data be stationary;

(2) The EMD gives a complete and orthogonal decomposition of the signal without missing or introducing any additional information into the signal. This merit is not met by both the FT and wavelet transforms;

(3) The EMD is locally adaptive to the inspected signal, which enables it to deal with the nonlinear signals more properly. By contrast, the FT uses a same time-frequency resolution in the whole process, and wavelet transform uses a same time-frequency resolution at the same scale level although it provides different resolutions at different scales.

In view of above advantages of the EMD in processing non-stationary, nonlinear signals with intra-wave natures, it is applied to analyzing WT signals in this work.

III. CONDITION MONITORING STRATEGY FOR WIND TURBINES

An efficient machine condition monitoring system relies on (a) the correct understanding of the machine and its subassemblies; (b) objective reliability information and the correct analysis of them; (c) the correct selection of critical components or subassemblies; (d) proper data acquisition techniques; (e) the correct analysis of monitoring data; and (f) a reasonable strategy for machine condition assessment. In addition, the capital cost of the designed system should be justified to the machine being inspected. For these reasons, it is very necessary to consider first which components and what signals of the WT should be inspected by a condition monitoring system before carrying out any further investigations.

A wind turbine system consists of thousands or even more number of components. Which of them should be monitored depends on their 'criticality', which is related not only to their failure rates, maintenance cost, but also to the economic losses they cause. In practice, the resultant economic loss is more cared by the industry in determining the criticality of a machine component. In this work, the economic losses caused by wind turbine subassemblies are approximated by the downtimes caused by failures. Fig.1 gives the annually average downtimes of major wind turbine subassemblies according to the LWK survey of more than 2000 wind turbines for 11 years [7].

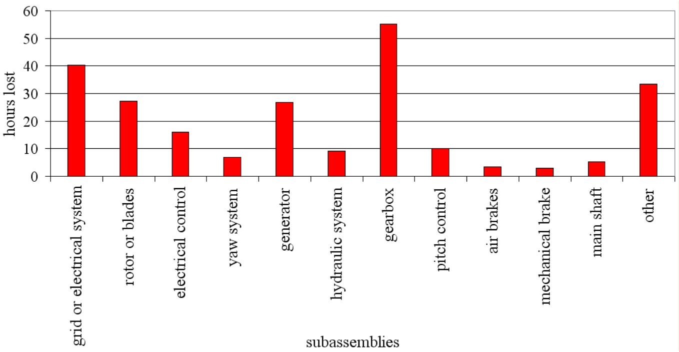

Fig. 1. Annual hour lost caused by wind turbine subassemblies.

From the statistic data shown in Fig.1, it is seen that gearbox, grid/electrical system, rotor blade and generator are ranked the 4 most critical subassemblies, which should be monitored with the first priority by a wind turbine condition monitoring system due to their high downtime caused. Currently, the commercially available condition monitoring systems have paid much attention to monitor these subassemblies. But unfortunately, most systems use vibration/temperature measurement, lubrication oil analysis and strain measurement approaches. These techniques are valid for detecting local mechanical failures, but not so successful to detect those electrical faults occurring in generator, converter/transformer and grid. Additionally, almost all available systems use Fourier transform-based techniques (e.g. envelop analysis [8]) to analyze the vibration signals measured from wind turbines, which is unable to manifest the signals accurately. Owing to the misinterpretation of the signals, the systems either fail to give alarm in the presence of a fault or give off spurious alarms in the absence of a fault. Thus, a new wind turbine condition monitoring technique is still needed today. For facilitating the explanation of the new wind turbine condition monitoring strategy proposed in this work, a diagram of a wind turbine with a two-stage gearbox is shown in Fig.2.

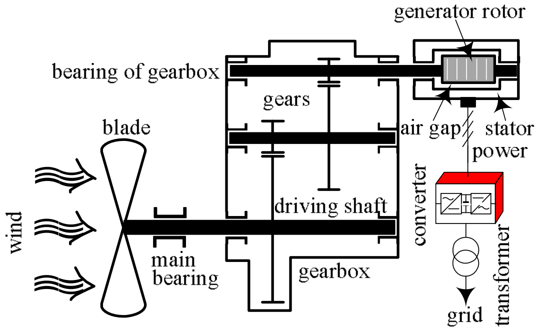

Fig. 2. Diagram of a wind turbine with a two-stage gearbox.

From Fig.2, it can be imagined that wherever the mechanical faults occur (either in blades, shaft, bearings or gearbox), the energy flow created by the fault travels along the drive train and in the end reaches the generator of the wind turbine. It will disturb the air-gap between the rotor and the stator of the generator and give response in the output (e.g. current and voltage) of the generator. Likewise, when an electrical fault occurs either in generator (e.g. stator/rotor winding fault), converter/transformer or grid, the output of the generator will be disturbed as well. This suggests that a globally effective way for detecting both mechanical and electrical WT failures may be achieved through monitoring the generator output. Obviously, this is a simple and cheap way without requiring any advanced sensors except voltage/current transducers. Moreover, the generator output signals have been already available in all types of wind turbines whether geared or direct drive. So, the proposed approach may be applied to all types of wind turbines. By contrast, most commercially available condition monitoring systems are only suitable for those gear driven machines, not for direct driven ones. In this work, the proposed approach is accomplished through analyzing the generator 3-phase total power signals by the EMD.

IV. TEST RIG AND EXPERIMENTS FOR FAULT SIMULATION

As shown in Fig.3, a wind turbine condition monitoring test rig was deliberately built for simulating various loading and running conditions of wind turbines. The test rig consists of a 30kW 3-phase induction generator with 2 pole pairs and a two-stage gearbox with gear ratio 1:5. The synchronous frequency of the induction generator is 50Hz. The test rig is driven by a 50kW DC motor, whose rotational speed is controlled by an external mathematical model in which both the nature of wind and the dynamic performance of the wind turbine driving shaft are incorporated. A tachometer was installed at the end side of the DC motor for measuring its real rotational speed. The rotational speed of generator rotor can be derived from the motor speed by taking into account the gear ratio. As shown in Fig.4, three current and three voltage transducers are installed in a cabinet for measuring the phase current and phase voltage signals output from the generator. In the experiments, both speed and electric signals are collected by using an NI DAQ card after they are preprocessed through a signal conditioner.

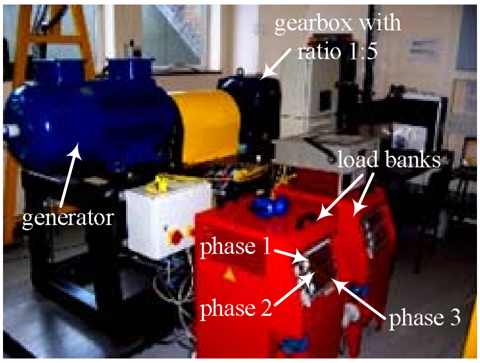

Fig.3. Wind turbine condition monitoring test rig.

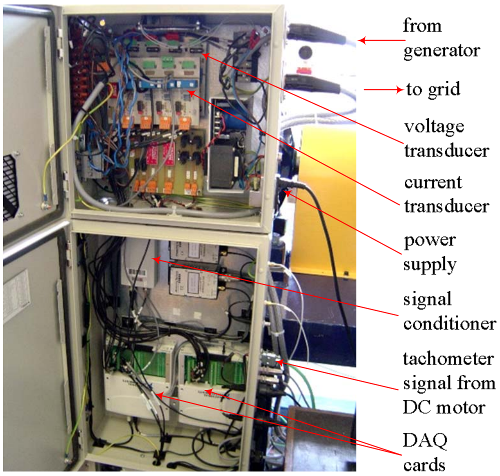

Fig.4. Data acquisition system.

Both a generator electrical and drive train mechanical faults were simulated on the test rig. The former is a circuit imbalance fault simulated by changing the phase resistances of the generator rotor with the aid of a load bank connected to it (see Fig.3); while the latter was a shaft imbalance fault simulated by directly attaching two unbalance masses to the shaft of generator rotor, as shown in Fig.5.

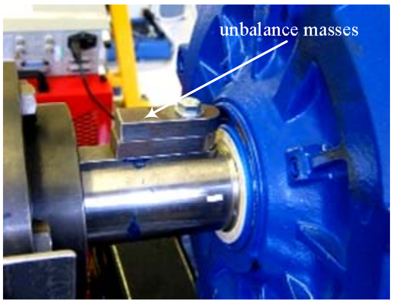

Fig.5. Simulation of a shaft imbalance fault.

V. CONDITION MONITORING USING THE EMD

5.1 Electrical fault

When the 3 phase resistances of the load bank were set unequally (e.g. to be 5.32Ω, 10.62Ω and 5.32Ω, respectively), an electrical imbalance was created between the phase circuits of the generator rotor. This imbalance fault can be removed immediately as soon as the load bank resistances are set equally.

In the experiment, the phase circuit imbalance fault was simulated for two times for verifying the effectiveness of the proposed EMD approach in fault detection. During the process, the rotational speed was variable for simulating the practical running condition of a real wind turbine. The 3 phase total power signal was collected from the terminals of the generator by using a sampling frequency of 3kHz. The time waveform of the obtained signal is shown in Fig.6.

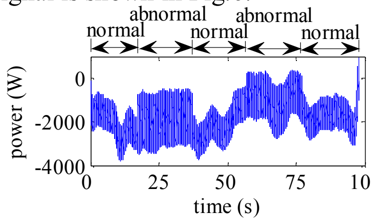

Fig.6 Total power signal when a phase circuit imbalance fault was simulated.

Obviously, the fault can hardly be detected through the direct observation of the signal waveform. In particular, the machine rotational speed varies constantly. Therefore, the EMD is applied to the signal and the IMFs obtained and their corresponding power spectra are shown in Fig.7.

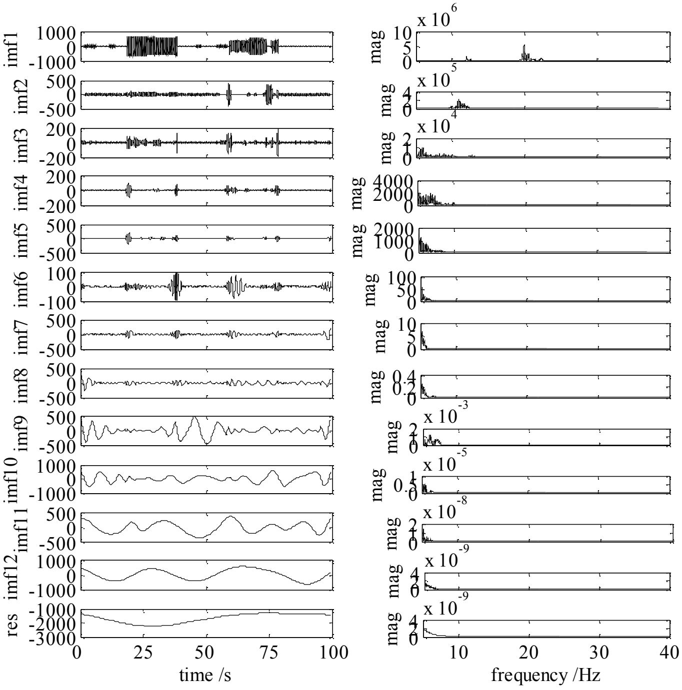

Fig.7 The IMFs for the power signal shown in Fig.6.

Refer to Fig.6, it is found that the first IMF in Fig.7 shows abnormal energy change in the presence of the phase circuit imbalance fault, while its energy decreases back to the original normal level (almost zero) as soon as the fault is removed. Moreover, Fig.7 shows that the first IMF obtained gives a sensitive and significant response at each time of the changing of machine condition. This phenomenon fully proves that the EMD is potentially a powerful tool for detecting the electrical faults occurring in wind turbine generator.

Additionally, from Fig.7 it is noticed that the fault-related energy change occurs in the first IMF, which corresponds to a frequency region centered approximately at 20Hz. In order to investigate the reason, the rotational speed of generator rotor, obtained by multiplying the rotational speed of DC motor with the gear ratio 5, and the calculated twice slip frequency of the generator are shown in Fig.8. It is necessary to note that the twice slip frequency is calculated by using the following equation, i.e.

$$2f_s = 2\times\frac{p\times\omega_r - \omega_s}{60}\,\text{(Hz)} \qquad (8)$$

where f_s is the slip frequency, p indicates the number of pole pairs of the induction generator, ω_r and ω_s respectively represent the rotational speed and the synchronous speed of the generator. They both are in the unit of 'rev/min'.

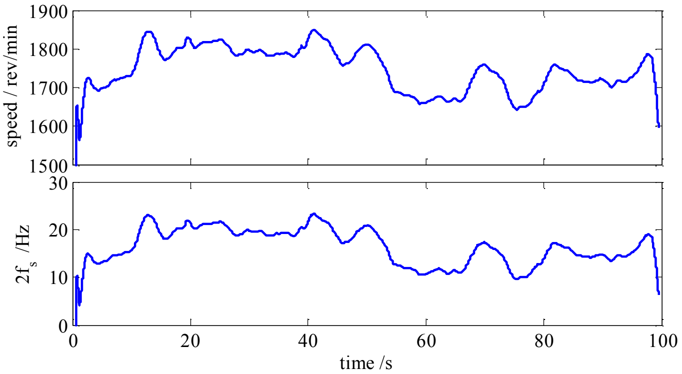

Fig.8 The rotational speed and twice slip frequency of the generator.

Apparently, the twice slip frequency of the generator fluctuates around 20Hz during the period. This suggests that a rotor or stator winding fault will create a significant twice slip frequency component in the generator total power signal. The creation of an opposing magnetic field in the rotor-stator air gap of the generator due to the unbalanced phase resistances accounts for the presence of the twice slip frequency. In turn, the twice slip frequency may be regarded as a characteristic frequency for detecting the sort of faults.

5.2 Mechanical fault

As shown in Fig.5, a shaft imbalance fault was created when two unbalance masses, one was 120g weight and another was 117g weight, were attached to the driving shaft of the generator. The generator total power signals were collected by using a sampling frequency of 3kHz before and after the unbalance masses were attached. Both signals are shown together in Fig.9 for facilitating the comparison.

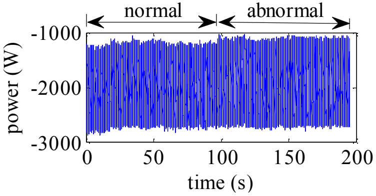

Fig.9 Total power signal collected before and after a shaft imbalance fault.

From Fig.9, no obvious difference may be observed from the power signal waveforms obtained before and after the shaft imbalance fault was simulated, although in this experiment the rotational speed of the generator rotor does not show significant fluctuation. Then, the EMD is applied to analyzing the signals and the resultant IMFs and their power spectra are shown in

Fig.10.

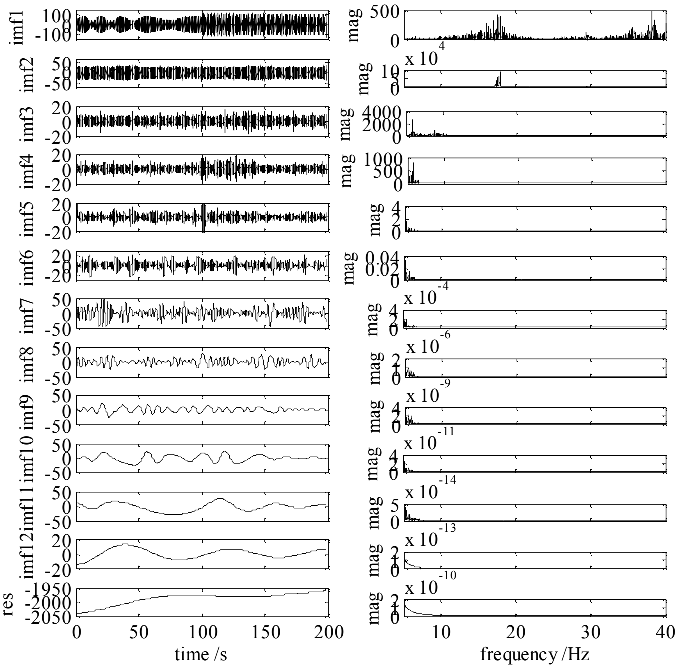

Fig.10 The IMFs for the power signal shown in Fig.9.

From Fig.10, it is found that in this experiment also the first IMF identifies the change of machine running condition due to the attachment of unbalance masses. It is noticed that the time waveform of the first IMF changes in both amplitude and geometric shape in the presence of the imbalance fault. But it is necessary to note that the low frequency amplitude modulation (about 0.06Hz) in the first IMF before the imbalance fault was applied should be false information created by the imperfect algorithm of the EMD. It has been noticed that during the process of the EMD, unidentified information may be occasionally generated at low frequency region [9]. This is a defect of the EMD in signal decomposition. But fortunately, this shortcoming can be ignored in machine condition monitoring because most faults occurring in high speed rotating machinery will not show so small a characteristic frequency (e.g. 0.06Hz).

The most interesting thing is that Fig.10 shows the fault-related energy change due to the mechanical imbalance fault occurs also at the twice slip frequency of the generator. This conclusion is reached from the joint analysis of Fig.10 and Fig.11. The latter clearly shows that the twice slip frequency of the generator fluctuates at around 16.8Hz, while the former shows that this 16.8Hz component dominates the first IMF. This phenomenon fully proves the previous prediction given in Section III, where it has been suggested that the mechanical faults occurring in the drive train of the wind turbine could be detected by power signal analysis because the energy flow created by the fault travels along the drive train and in the end reaches the generator and disturbs the rotor-stator air-gap. In consequence, an opposing magnetic field will occur due to the dynamic eccentricity between the rotor and the stator, and finally result in a twice slip frequency component in generator power signal [10].

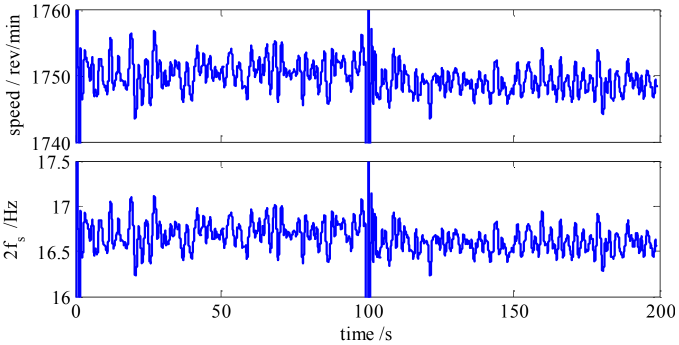

Fig.11 The generator rotational speed and its twice slip frequency.

VI. CONCLUDING REMARKS

The aforementioned work shows that the EMD is potentially a power tool for the condition monitoring of wind turbines as the resultant IMFs is always able to give an obvious indication of the change of machine running condition. Additionally, the twice slip frequency of the generator may be regarded as an important characteristic frequency for condition monitoring as it would appear whether a drive train mechanical or a generator electrical fault occurs in the wind turbine.

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